LABORATORY MANUAL IN PHYSICS

LABORATORY MANUAL IN PHYSICS

BY

A. A. KNOWLTON, Ph.D.
Professor of Physics, Reed College

AND

MARCUS O'DAY, Ph.D.
Assistant Professor of Physics, Reed College

Second Edition

McGRAW-HILL BOOK COMPANY, Inc.
NEW YORK AND LONDON
1935

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE TO THE SECOND EDITION

With the exception of Exercises 11, 12*a* 26, 27, and 51 the material is identical with that in the First Edition. The order of topics has been changed to agree with that in the Second Edition of *Physics for College Students* and all page and chapter references have been corrected to refer to that edition.

A. A. KNOWLTON.
MARCUS O'DAY.

PORTLAND, ORE.
September, 1935.

PREFACE TO THE FIRST EDITION

Why should students of general physics be required to do laboratory work? This question is being rather persistently asked by the non-scientific members of college faculties and by administrators. Critics of the laboratory are likely to explain that they are interested in a set of conditions which will enable non-scientific students to get "a broad general knowledge of the great principles and theories of physical science." This is certainly a reasonable desire and, if the laboratory does not contribute to this end, it will probably have to go, so far as such students are concerned. The recent popularity of courses *about* science (usually designated as "science survey courses") is an illustration of the modern trend.

Physics has an unenviable reputation for difficulty. This difficulty is often charged to "mathematics," whatever that may mean. An analysis of student troubles seems to the authors to indicate that the difficulties are, in a great majority of cases, due to the multitude of new concepts (abstract ideas) to which the student of general physics is unavoidably introduced at the very outset.

As an illustration consider the following problems:

a. A housekeeper buys 8 pounds of sausage at 25 cents per pound and 8 pounds of potatoes which sell at the rate of 32 pounds for a dollar. What is the total cost?

b. A box weighing 8 pounds is moved along a rough floor, the coefficient of friction being 0.25, and is at the same time accelerated 1 ft./sec.² What force in pounds is required?

The solutions may be written out as follows:

a. Cost of sausage + cost of potatoes = total cost.

$$8 \times 0.25 + \frac{8 \times 1}{32} = \$2.25$$

b. Force to overcome friction + force to accelerate = total force.

$$8 \times 0.25 + \frac{8 \times 1}{32} = 2.25 \text{ lb.}$$

The reasoning and the arithmetical work involved in the two solutions are identical; but the second problem deals with

unfamiliar ideas and is, for that reason, far more difficult. And the difficulty cannot be avoided. The fundamental concepts of physics—force, acceleration, etc.—must become familiar to the student before he can acquire that "broad general knowledge of physical principles and theories" which the critics of the laboratory method desire. This necessity is as inescapable as the need for the acquisition of a French vocabulary and some knowledge of the technique (grammar) of the French language if one wishes to read the works of Anatole France in the original.

There is another point of importance about physical concepts. They are new in kind as well as new individually. For the most part they are quantitative, or perhaps it is better to say metric, in character; that is, *the concept is defined by the method used in measuring the thing defined.*

Herein lie the necessity and the justification for quantitative laboratory work. A laboratory is a place for the acquisition of those metric experiences which are a necessary background for metric concepts; a place in which the student may clarify his ideas of physical quantities through a first-hand experience with measurable things, thus giving a kind of bodily reality to the unfamiliar names which occur in his textbook.

Such a view of the function of the laboratory entails certain rather obvious consequences of which only those which have been determinative in the preparation of this manual need be indicated.

1. Laboratory work should be truly individual in the sense that each student should at all times be doing work appropriate to his own needs. This means that there can be no set list of exercises which all must do. On the contrary, there is need of a graded selection of exercises covering the more important and troublesome concepts, and choice must be made from this list as individual needs demand.

2. Requirements of technique should be reduced to a minimum.

3. The student should be taught to think of each exercise as a coherent unit dealing with a worth-while idea, rather than as an exercise in measuring some wholly unimportant quantity. The test of success in an exercise lies in the clearness of the student's ideas when it is completed rather than in the numerical accuracy of his results.

4. Much assistance should be offered at the beginning and less later.

In an attempt to meet these needs, this manual contains some two or three times as many exercises as a student is likely to do in the first-year course. The exercises vary greatly in difficulty and cover a considerable range of concepts. Finally, a definite attempt has been made to present the material in such a way that the attention of the student may be directed to the meanings rather than to the minutiæ of the exercise.

Reports.—The authors' habit is to tell the student that the laboratory report should be a brief essay concerning the topic under consideration. In it, he should tell what he did, what results he got, and what he thought about the topic. His data are to be used to illustrate points in the essay. In a few of the earlier experiments, specific directions as to the methods of recording data and the forms of reports have been given as examples.

Aids to Computation.—The laboratory should be provided with several copies of books containing logarithms and other mathematical tables and with a copy of the "Handbook of Chemistry and Physics,"[1] to which frequent reference is made. It has seemed better not to include abbreviated tables in the manual itself inasmuch as this would increase the cost of the book and at the same time furnish a less satisfactory set of references. The use of the "Handbook" has an added value in that the student learns where data as to physical quantities of all sorts may be found. The use of slide rules should be encouraged and a calculating machine provided for use where very long computations are required. Such helps reduce the drudgery of computations, which is one of the bugbears of many laboratory exercises.

The authors wish to express their thanks to the Central Scientific Company, L. E. Knott, Leeds, Northrup & Co., the Welch Scientific Company, and the Weston Electrical Instrument Company for assistance in preparing the illustrations.

A. A. KNOWLTON.
MARCUS O'DAY.

PORTLAND, ORE.
February, 1930.

[1] Chemical Publishing Company.

CONTENTS

LABORATORY MANUAL IN PHYSICS

GROUP I

THE FUNDAMENTAL QUANTITIES OF MECHANICS

(Pages 40–42)[1]

All mechanical changes resulting from the action of one body upon another may be described in terms of the distance between two points, the time interval required for the action, the quantities of matter in the bodies, and the forces acting between them. It follows that the measurements of lengths, time intervals, quantities of matter, and forces are of fundamental importance in all physical observations. It is the object of the exercises in this group to acquaint the student with some of the instruments and methods which will enable him to make these fundamental measurements rapidly and with accuracy. In connection with the results of the observations, some attention is also given to the important problem of estimating the degree of reliability of measured quantities.

Exercise 1

THE MEASUREMENT OF A LENGTH

Apparatus.—Two meter sticks, two square-edged blocks for markers, vernier calipers, several small metal cylinders, micrometer caliper, wire gage, wires.

In the general physics laboratory lengths are nearly always measured directly, that is, by the direct comparison of the measuring instrument with the length to be measured. This may be contrasted with the indirect methods often used in surveying, in which the distance between two points is determined

[1] Pages refer to KNOWLTON, "Physics for College Students," 2d ed.

by the measurement of an angle and a second length. For the beginner, the most important, because the most frequently used, instrument for the measurement of lengths is the ordinary meter stick or ruler. The accuracy obtainable with this simple instrument in the hands of a careful worker is really surprising.

A. The Metric System.—If you are not already familiar with the metric system, begin by trying to acquire some such familiarity. Lay the two meter sticks side by side with the inch scale of one in contact with the metric scale of the other and make the following approximate comparisons.

How does the meter compare with the yard?

How many centimeters are there in 1 ft.?

How many centimeters in 1 in.? How many millimeters?

To about how many millimeters is $\frac{1}{8}$ in. equal?

B. To Measure a Short Length as Accurately as Possible with the Meter Stick.—The particular problem is to measure a 10-in. length in centimeters and to compute the number of centimeters in 1 in. from the mean of these measurements.

Place the two meter sticks side by side with the inch scale of one and the centimeter scale of the other up. Set the centimeter scale so that an even 10-cm. mark is *exactly* opposite some selected inch mark on the other scale, and take the reading opposite the mark 10 inches away, *estimating tenths of millimeters.* Record as shown:

Inch scale	Centimeter scale	Number centimeters in 10 inches
20.00	21.00	
30.00	46.45	25.45

Make and record in the same way four more determinations using different parts of the sticks each time. Exchange the two sticks and repeat. Average the ten results thus obtained and determine the probable error of a single measurement and of the series by means of the formulæ

$$\text{Probable error (single measurement)} = 0.67\sqrt{\frac{r_1^2 + r_2^2 + \cdots}{n - 1}}$$

$$\text{Probable error (series)} = 0.67\sqrt{\frac{r_1^2 + r_2^2 + \cdots}{n(n - 1)}}$$

In these formulae n is the number of observations (10 in this case) and r_1, r_2, etc. are the *residuals* or amounts by which the corresponding readings differ from the arithmetical mean of the series.

In making these computations treat the residuals as whole numbers; *i.e.*, disregard the decimal point in the readings. Use tables of squares and square roots like those in the "Handbook of Chemistry and Physics," and take values of the radicals to the nearest whole number only, since no greater accuracy is justified. Finally, restore the decimal point. Compare the mean value of the length of 1 inch in centimeters (one-tenth your average) with the correct value (1 in. = 2.540 cm.) and compute the percentage of error in the determination. Remembering that an error of 1 per cent means one part in 100, etc., make a statement like the following, basing the numerical part on your own data: *It is possible to measure lengths of about a foot with an accuracy of* 1 *part in* 2,000 *by the use of a meter stick.* Does this increase your respect for the meter stick as a measuring instrument? If the absolute magnitude of the errors remains the same, what would be the percentage error in measuring a length of 1 cm.?

There are several points worth noting in connection with the methods described above.

a. In the first place, no two meter sticks are exactly alike. Small errors of graduation are unavoidable in even the best of instruments and these may be considerable in such cheap instruments as wooden meter sticks. The procedure outlined in which different parts of each stick are used and the two sticks interchanged tends to make these "instrumental errors" offset one another.

b. The ends of the meter sticks were not used because they are usually rounded off so as to introduce a considerable error.

c. Errors of reading are minimized by placing the two sticks in contact. Taking a number of independent readings tends to cause the errors of estimating tenths of millimeter to offset one another.

d. All readings should be so recorded as to show the degree of accuracy. Students are inclined to record only the whole number part of a reading like the inch readings. The two zeros at the right of the decimal point in the table are an indication that the readings have been made to hundredths of an inch.

Every reading recorded should show the accuracy with which it is made. To say that a given length is 20 in. is not the same as to say that it is 20.0 or 20.00 in. The length may be the same in all three cases but there is an important difference in the statements.

C. To Measure a Length Greater than One Meter as Accurately as Possible with a Meter Stick, and to Learn How the Values of Computed Quantities Are Affected by Errors in the Measured Quantities.—The particular problem is to measure the length and width of a table and to determine the most probable value of its area upon the assumption that it is a perfect rectangle.

Lay one of the meter sticks along the edge of the table so that it projects slightly over one end. Hold a square-edged block

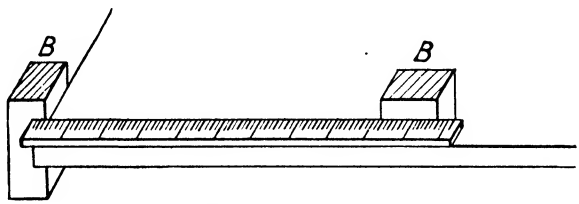


FIG. 1.—Method of using meter stick.

firmly against the end of the table and adjust the stick until the 1-cm. mark (or any other even centimeter mark) is exactly in line with the face of the block. Hold the stick firmly in position and place the edge of a second block at some whole centimeter mark near the other end of the stick as shown in the Fig. 1. Read and record the position of the right hand edge of this block, then slide the stick along until the 1-cm, mark is exactly even with the same edge. Repeat, if necessary, until the stick projects over the other end of the table, and determine this last reading to tenths of millimeters by using the block against the end of the table. Record the readings as shown:

Left end........	1.00	
Block...........	91.00	90.00
Block..........	1.00	
Right end.......	93.67	92.67
Length...............		182.67

Make and record four more such determinations of the length and a series of five determinations of the width. Estimate the

probable error of the means by the use of the second formula above and express this as percentage error. If, for example, the probable error of the length (in the example above) is 0.05 cm., the percentage error is seen to be approximately equal to 5 parts in 18,000, or 0.03 per cent. If the percentage error in determining the width is 0.05 per cent, it can be shown that the product of these two will be subject to a percentage error of 0.08 per cent. That is, *the percentage error of a product is equal to the sum of the percentage errors of its factors.* This may be illustrated (not proved) if it be assumed that the true value of each of two factors is 100 while the measured values are each 101. Here the percentage error in each factor is 1 and the computed value (10,201) is evidently in error by almost exactly 2 per cent.

Computing the Area.—In a particular case, the length and width of a table were found to be 182.67 cm. and 123.43 cm. with a probable error of 0.05 cm. in each case. The usual procedure of computing the area thus requires the multiplication of one five-figure number by another. This rather tedious process may be considerably shortened without loss of accuracy. Consider the following computations:

(*a*)	182.67	(*b*)	182.67	
	123.43		343 21	
	5 4801		18267	$= 1 \times 18267$
	73 **068**		3654	$= 2 \times 1827$
	548 **01**		549	$= 3 \times 183$
	365**3 4**		72	$= 4 \times 18$
	18267		6	$= 3 \times 2$
	2254**6.9581**		22548	

In (*a*), the multiplication has been carried out in the usual way. Since the last figure in each factor is doubtful, it follows that each of the bold-faced figures below is also doubtful, and the product is therefore unknown beyond the first uncertain figure which is the **6**. Obviously, a great deal of work might be saved if such multiplications could be performed in such a way as to leave out all the useless figures which lie to the right of the vertical space. This can be done by performing the operations as in (*b*). Here the multiplier has been written in the reverse order, and in multiplying by any digit of this reversed number, all figures of the multiplicand which lie to the right of that digit are disregarded (except that, if the first neglected figure is 5 or greater, we increase the figure above by 1), and the partial

products are arranged so that the right-hand figures are in line. The product is seen to be the same as that obtained in the usual way out to the doubtful figure. It is worth while to realize that the product in (*b*) is really quite as reliable as that in (*a*). The area of the table is 22547 $\pm$ 0.08 per cent and, since 0.08 per cent of 22547 is 18, this really means that no better than a fifty-fifty assurance is felt that another determination made with equal care would lie between the limits of 22529 and 22565. One of the most important parts of any measurement lies in the estimation of its accuracy. One who based any important conclusion upon the supposition that he knew the area of the table top in the previous discussion to the precision indicated by the figures obtained from the full multiplication (22547.9581) might find himself seriously astray. *It is an important part of knowledge to know where knowledge ends.*

The principles here developed should be applied in all future work. In general, it will not be necessary to go into any great detail to determine the probable error with sufficient accuracy for our purposes, but some estimate of the errors to be expected should always be made and the final result ruthlessly pruned to the point where it shows what is really known. Wherever possible it is wise to compare your results with known correct values, and compute the percentage by which your results differ from these.

D. The Vernier.—The vernier (named after its inventor, Pierre Vernier, a French engineer) is a device for measuring (instead of estimating) fractions of the smallest scale division of the instrument to which it is attached. It is simply an auxillary scale the divisions of which are slightly smaller than those of the standard scale over which it moves. In the special case in which it is desired to measure the tenths of the smallest scale division, tenths of millimeters for example, each vernier division is nine-tenths as long as the scale division, so that ten vernier divisions (V) are equal to nine scale divisions (S)

$$10V = 9S$$

In this case, it is evident that if the first and last marks on the vernier are each exactly opposite a mark on the scale, the second mark will be one-tenth of a scale division to the left of the corresponding mark on the scale, the next vernier mark two-tenths to the left of the corresponding scale mark, and so on.

Thus, if the first mark (zero mark) does *not* lie opposite a scale mark, its distance to the *right* of such a mark can be determined by finding the vernier mark which *does* lie opposite a scale mark. *In using the vernier, the scale is read as usual up to the last mark to the left of the zero mark of the vernier, and tenths of divisions are added from the vernier by simply counting the vernier spaces up to the point where a vernier mark lies opposite a scale mark.*

Use of Vernier Calipers.—Examine the calipers (Fig. 2) and make a few practice settings with them until sure that you can read them quickly and accurately. Note that these calipers are provided with jaws for measuring the inside diameters of tubes, etc., and with a slide to be used for measuring the depth of

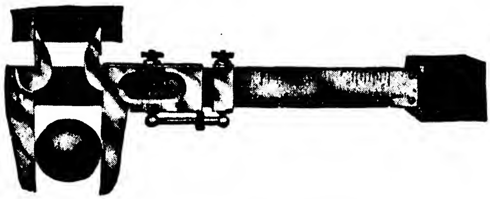


FIG. 2.—Vernier calipers.

vessels, as well as with jaws for measuring outside diameters. Measure the length and diameter of each of the cylinders, making five independent settings on each. Read the barometer using the vernier's in both inches and centimeters. Reduce the barometer height in inches to centimeters, as a check on the accuracy of the readings.

E. The Screw as a Measuring Instrument.—A divided circle attached to an accurate screw forms the essential part of many instruments for precise measurements. The forms are very numerous and the accuracy attainable limited only by the accuracy with which screws can be cut. The micrometer caliper, extensively used by machinists, is the most widely known of such instruments (Fig. 2a). In the laboratory instruments, the screw usually has a pitch of ½ mm. (*i.e.*, moves forward ½ mm. when turned once around), and the head is divided into 50 equal parts so that each division indicates an advance of 0.01 mm. Full turns are indicated on a scale covered by the head. While the theory of the instrument is easy, its use requires considerable skill which can be obtained only through practice. The first point is to make sure of the reading of the instrument, *i.e.*, as to what the graduations indicate. The second step is to check the zero

point. If the instrument does not read zero when turned down against the stop, it will be necessary to determine the "zero correction" which must be added to or subtracted from all readings. Unless the instrument has a friction stop (ratchet), which automatically limits the pressure, it is necessary to be careful that the screw is always turned down with the same pressure. In use, the zero should be checked frequently, to be sure that no dirt or dust has been picked up to alter it. With care, settings may be made and readings taken so closely that the estimated tenths of head divisions are significant. Since one-

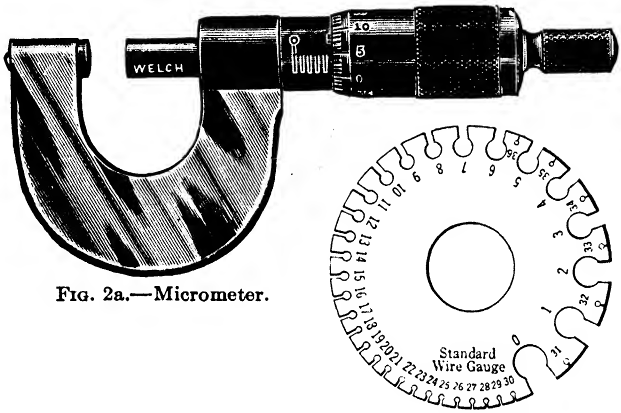


FIG. 2a.—Micrometer.

FIG. 2b.—Wire gage.

tenth of a division corresponds to 0.001 mm., even a rather small dust particle may cause trouble. Since the screw may be slightly loose in the nut, it is important that all readings should be approached from the same direction, thus avoiding errors due to this defect, called "backlash."

Measure the diameters of the wires provided and check by use of the wire gage (Fig. 2b). In using the gage, the wire is slipped into the slot *sideways*. The number of the wire is that of the smallest slot into which it can be put. Diameters corresponding to these numbers are on the back of the gage. Compare the measured diameter with those corresponding to the numbers as determined from the gage. Is there any systematic difference?

NOTE.—There are several wire gages in use—all arbitrary. The one most generally used in this country is the Brown and Sharpe (B. & S.) or American Wire Gage (A. W. G.). Notice that with this gage the diameter doubles with the decrease of 6 in the gage number. Check this statement.

Tabulating Observations and Results.—All observations and computed results should be neatly arranged and tabulated so that related values can be seen at a glance. Final results, like the area of the table top, may be underlined, thus to bring them into prominence. In this exercise, the tabulated data and results are the only report required. All computations should be completed before going on to other work. Form the habit of recording data at once in its proper place and form without copying.

Exercise 2

MASS, WEIGHT, DENSITY

(Pages 23, 41, 58–63, 136–138)

Apparatus.—Chemical balance, weights, three objects to be weighed, vernier caliper, micrometer, graduate, thermometer, and barometer.

The need of accurately comparing quantities of matter arises with great frequency both in the laboratory and in everyday life. Everyone is familiar with the process of weighing sugar, coal, etc. and realizes that it is done for the purpose of assuring the purchaser that he is receiving a definite quantity of the material weighed. That is, the process of *weighing* is usually carried out for the purpose of determining the *quantity of matter* in some particular body. This enables us to attach a definite meaning to the phrase *quantity of matter;* and, in physics, the word *mass* is defined as meaning *the quantity of matter as determined by weighing.* The concept thus defined proves to be one of the most important in the whole field of science.

The weight of a body is the force with which it is attracted toward the earth, and the unit of weight is the force with which the earth attracts a certain arbitrarily selected block of matter. Thus the visible standards which are called "weights," are really standard masses, *i.e.*, bodies containing definite quantities of matter; and the process of weighing is merely the process of determining the number of such standard masses which are attracted toward the earth with a force equal to that acting on the unknown body at the same place. It is important to notice that in the process of weighing, equality of masses is inferred from equality of forces.

The equal-arm balance is the oldest, simplest, and most instructive type of apparatus used for weighing. Such balances

were in use at the time of the construction of the pyramids, in forms not very unlike some present-day instruments. The

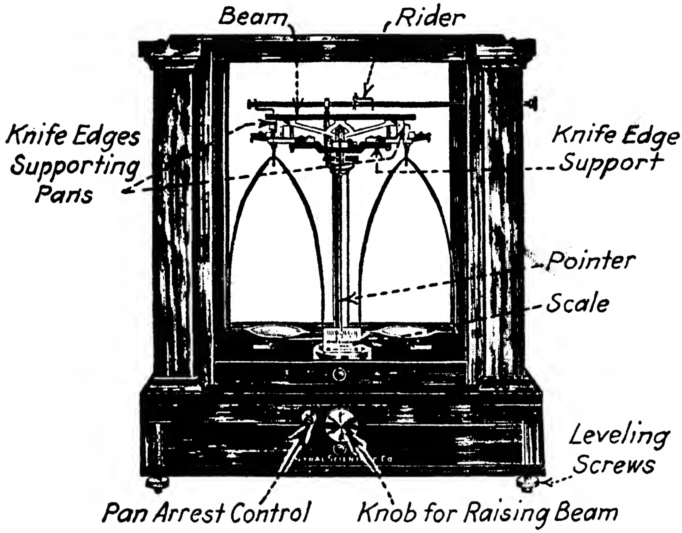


FIG. 3.—Chemical balance.

operation of such a balance affords an excellent illustration of the principle of equilibrium of moments discussed in Chaps. VI and VII of the text. In the highly developed form which will be used, the balance consists of a light, rigid *beam* carrying two *pans* and

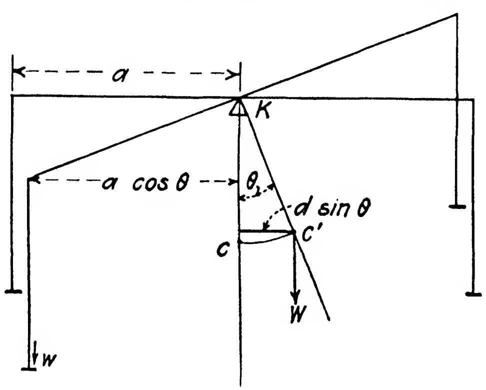


FIG. 4.—Equilibrium of moments in the chemical balance.

mounted so as to turn freely upon an agate *knife edge*. Figure 3 shows the essential parts of such a balance designed for accurate

laboratory work. Compare this figure carefully with the balance with which you are to work in order that you may become familiar with the parts of the latter and with the terms used in connection therewith. The application of the principle of rotational equilibrium to such a balance is shown in Fig. 4.

The addition of a small weight w to one pan in excess of that in the other causes the beam to rotate about the knife edge K until the torque due to the added weight is exactly balanced by that due to the weight W of the beam itself. If the center of gravity of the beam is originally at c, d cm. below K, it will move to some new position c' such that

$$wa \cos \theta = Wd \sin \theta$$

or

$$\frac{a}{Wd} = \frac{\sin \theta}{w \cos \theta} = \frac{\tan \theta}{w}.$$

$\frac{\tan \theta}{w}$ is defined as the sensitiveness of the balance.

Preliminary Manipulation.—The first step in the use of any unfamiliar piece of apparatus is to establish a certain degree of acquaintance with it and, in particular, to learn about its controls; *i.e.*, to find out what happens when a particular button is pushed or a particular knob is turned. It will pay you to spend a few minutes in getting acquainted with the balance before attempting to master the technique of its use. Remember that it is a delicate and rather costly instrument of precision and treat it accordingly. In particular, avoid any jarring, and never touch the moving parts with anything except the camel's-hair brush as directed later. Keep the case closed except during the initial stages of weighing, and be sure that the beam is off the knife edges at all times except when an observation is actually being made. If any adjustments seem necessary, let the instructor show you how to make them.

If there is a level attached to the balance case, the first step is to see that the instrument is accurately leveled. If there is no attached level, it may be assumed that this adjustment has been made by the instructor. Lower the beam and note that the pointer swings back and forth across the scale with a slowly decreasing amplitude. To wait for it to come to rest would make weighing a slow process and the results would be affected by errors due to friction. For these reasons, accurate weighings are made by the "method of vibrations."

Determination of the Zero Point.—The first step is to find the rest point of the empty balance, *i.e.*, the position on the scale at which the pointer would come to rest if the vibrations were allowed to die out completely and if there were no friction. This is conveniently designated as the *zero point*. The scale should be marked as in Fig. 5. Be sure that the rider is off the beam and free from it, and that the pans are free from dust. If necessary, the pans may be brushed off with a small camel's-hair brush. If this is done, be sure that the beam is off the knife edges and that the pan arrests are released before touching the pans.

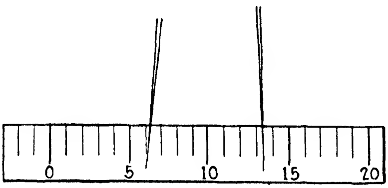


FIG. 5.—Method of reading balance deflection. The turning points shown are 6.2 and 13.3.

Release the beam and set it in motion so that the pointer swings over a little more than five divisions on each side of the rest point. If the swing, on gently lowering the beam, is not of the right magnitude, it may be regulated by touching the right-hand pan *very lightly* with the brush. Any pendulum-like swing of the pans must be stopped by touching the side of the pan.

Close the case and allow the balance to make two or three swings before beginning to read. This allows time for air currents within the case to die out. Now read five successive turning points of the pointer, estimating tenths of a division in each case, and record them as shown.[1]

DETERMINATION OF ZERO POINT

	Readings	
	Left	Right
	4.9	
		15.1
	5.0	
		15.0
	5.2	
	3)15.1	2)30.1
Means	5.03	15.05

Mean reading left	5.03
Mean reading right	15.05
	2)20.08
zero point	10.04

[1] The student will understand that in this and other places where data is given it is merely illustrative. Neither his readings nor his rest point will be exactly like these in the table.

Repeat this determination several times and take the average as the zero point of the balance. From an inspection of your results state the approximate probable error of a single determination of the rest point. In accurate weighing it is necessary to redetermine, or at least to check, the zero point each time the balance is used. A little consideration will enable one to understand why an odd number of readings must be taken.

Approximate Weighing.—The next step is to determine the approximate weight of the body used. This leads to a consideration of the weights themselves. If you are not already familiar in a practical way with the weights of the metric system, here is the place to acquire some real notion of their magnitudes. The weights of a set are contained in a box having a place for each weight from 50 or 100 g. down to 5 or 10 mg. Examine the set given you to be sure that it is complete and that all weights are in good condition. *You will be held responsible for the return of the set in perfect condition.* There are three rules for handling such weights which should never be violated.

1. Never touch any weight with the fingers. Handle them with the forceps provided for the purpose.

2. Never put a weight down anywhere except on the pan of the balance or in its proper place in the box.

3. Be careful not to bend the fractional weights. Pick them up by the turned-up edge or corner, never in any other way.

Place the object to be weighed on the left-hand pan and set the box of weights in front of the right-hand side of the balance.

Put a weight which you think to be greater than that required on the right-hand pan and carefully release the beam *just far enough to allow the pointer to move about two divisions* from its rest point. As soon as the direction of deflection is determined raise the beam without allowing it to swing farther from its position of rest. If your selection of a weight was right, the pointer should swing toward the left. In this case remove the weight, and try the next smaller one in the same way. If the weight of the body is between the two values the deflection will now be toward the right; if not, try the smaller weights in succession until a reversal is obtained. Continue in this way until you have on the pan a weight which is *less* than that of the unknown by not more than 10 mg. Further balancing is to be done by means of the rider. The key to rapid weighing lies in the rapid trial and rejection of

weights during this preliminary process. Two or three minutes ought to be sufficient for this weighing to centigrams.

Use of Rider.—In the usual type of balance, the final adjustment is made by moving a small weight in the form of a rider along the divided beam. The rider usually weighs either 10 or 12 mg. and the beam is so divided that adjustments may be made to $\frac{1}{10}$ mg. In order to be able to place this rider in the required position without loss of time one must determine the *sensitiveness* of the balance; that is, the change in rest point which results from the addition of 1 mg. to the right-hand pan.

When the weight has been determined to less than 10 mg. as directed above, close the balance case, place the rider on a numbered division, and determine the rest point as previously directed by a single set of five readings. Move the rider one full division in the direction which will move the rest point toward the "zero point" and again determine the rest point. The difference between these two rest points is the *sensitiveness* and as soon as this is determined one can compute the change in position required to balance the beam. An illustration is given below:

Zero point..................	10.04	Required change...	0.60 division
Rest point, rider on 4.......	10.64	Sensitiveness......	(10.64 − 9.70)
Rest point, rider on 5.......	9.70		0.94 division per milligram

Change of weight required $\frac{60}{94}$ or 0.6 mg. to be added.

Set the rider at the indicated point on the beam and check the rest point. If it is as much as 0.1 division from the zero point, move the rider by the indicated amount and check again.

Counting Weights and Recording Weights.—In order to avoid possible errors in recording the weights, they should be counted and then checked on removal, the value of each weight being set down and checked. One may either count the weights on the pan or, rather more easily, those absent from the box. The checking should be done as the weights are removed from the pan. The record will then look as follows:

Weight of Iron Cylinder No. 3

20.000✓
10.000✓
2.000✓
0.200✓
0.100✓
0.010✓
0.0043 (rider)
32.3143

The Concept Density.—Density is defined as mass per unit volume so that

$$D = \frac{M}{V}.$$

Measure the dimensions of the regular bodies which you have weighed, using either a vernier caliper or micrometer according to the size of the object and compute the approximate density of each material used. The volume of any irregular object may be found by putting it into a graduated cylinder partly filled with water and noting the change in level of the water.

Correction for Bouyancy of the Air.—Every body immersed in a fluid has a tendency to float; *i.e.*, is acted on by an upward force due to the action of the fluid upon it. It is shown ("Archimedes Principle," p. 218 text) that this bouyant force is equal to the weight of the fluid which the body displaces.

Since both the body weighed and the weights are acted upon by such upward forces due to the weight of the air which they displace, it is apparent that, had the weighing been done in a vacuum, a slightly different value (the weight in vacuo or true weight) would have been obtained. These corrections are negligible in ordinary commercial weighings but are appreciable where the precision is that attained in this exercise. If we let V stand for the volume of the body weighed, v for the volume of the weights, and d for the density of the air, it is evident that the correction (Δw) ought to be given by

$$\Delta w = (V - v)d.$$

The volume of the weights may be found from a knowledge of the fact that they are made of brass with a density of 8.4 gm. per cubic centimeter. Read the barometer and thermometer and look up the corresponding density of air in the "Handbook."

Compute the correction to be applied to each weighing and record the true value of the mass of each body. Also, compute the true density of each material. Is the accuracy of such a density determination limited by the accuracy of weighing or by the accuracy with which you have determined the volume of the body?

Exercise 3

MEASUREMENT OF FORCES. CALIBRATION OF A SPRING

(Page 252)

Apparatus.—Joly balance, small weights, objects to be weighed, commercial spring balance and larger weights.

The primary ideas of force seem to be derived from muscular sensation, and the everyday units of force, like pounds, kilograms, etc., are measures of the forces required to lift certain definite pieces of matter (standard masses). Devices used for the measurement of forces are often called "dynamometers." The most familiar example is the ordinary spring balance. All such instruments are calibrated in terms of the graviational units—pounds, kilograms, etc. Our particular problem is to learn how the elongation of a spring varies with the load which is added to it, and to calibrate a particular spring so that it may be used for measuring forces. The apparatus is shown in Fig. 6. Examine it carefully and become familiar with its operation before beginning to make readings.

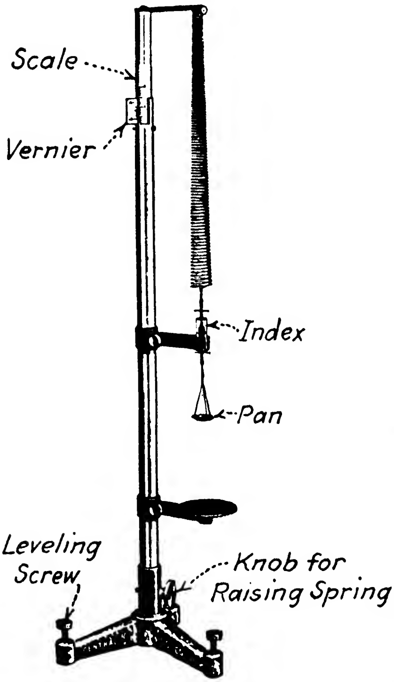


Fig. 6.—Joly balance.

A. Level the stand and adjust the tube carrier so that the index hangs freely within the tube when the pan is empty. Note that the index mark on the glass tube goes all the way around. The proper adjustment is made when the middle of the three white lines on the index is in the same horizontal plane as this mark. Make this adjustment with no load in the pan and read the vernier. Repeat twice, recording each reading. Add a small weight (0.5 g. if the spring is a rather light one, 1.0 g. if the spring is stiffer) to the pan; return index to proper position, and again read the vernier. The difference between the two readings is the amount by which the added load has stretched the spring. Repeat the setting twice and take the average. Continue in this way until five loads have been added. Plot a curve using loads as abscissæ and elongations as ordinates. What does this show as to the relation between these two quantities? This relation is known as "Hooke's law."

What is the *force constant* (*i.e.*, the force required to stretch it 1 cm.) of your spring? Weigh each of the small bodies supplied with the apparatus. How does the accuracy of this spring balance compare with that of the chemical balance?

METHOD OF TABULATING DATA. JOLY BALANCE

Weight (grams)	Vernier settings			Elongation	Elongation per gram
0	0.07	0.08	0.07		
2	5.88	5.87	5.88	5.81	2.905
4	11.67	11.67	11.67	11.60	2.905
5	14.68	14.69	14.70	14.62	2.924
6	17.59	17.59	17.60	17.52	2.920

B. Check the scale of a commercial spring balance by hanging a number of known weights from it and plot a curve showing the relation between *weights* and *readings*. In particular look for any zero error; *i.e.*, error of the reading when the balance carries no load. In tabulating, indicate corrections to be subtracted (balance reading too high) by a minus sign. How closely could you weigh a body on this balance? What advantages has it? What important disadvantage?

If you were to buy gold in Alaska and sell it in San Francisco would it be to your advantage or otherwise to use a spring balance which had been calibrated in Washington D. C. rather than an equal arm balance?

METHOD OF TABULATING BALANCE CORRECTIONS
Zero correction. +2 grams

Added weights	Balance readings	Corrections
50 grams	50 grams	0 grams
100 grams	99 grams	+1 grams
200 grams	198 grams	+2 grams
300 grams	297 grams	+3 grams
400 grams	396 grams	+4 grams
500 grams	496 grams	+4 grams

GROUP II

SIMPLE CONCEPTS OF MECHANICS

Exercise 4

THE LAWS OF FRICTION

(Chapter V)

Apparatus.—Spring balance, weights, three metal toboggans, metal plate. (The sliders or toboggans may be conveniently made by bending strips of tin or galvanized iron of three different widths into the form shown in Fig. 7.)

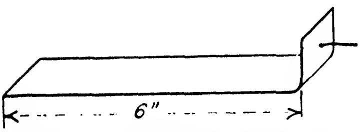


FIG. 7.—Toboggan for experiment on friction.

This is a simple exercise in the measurement of forces, involving the concepts connected with the subject of frictional resistances.

Zero Correction of the Balance. When the balance is used in a horizontal position, the spring is not stretched by the weight of the hook and other attachments so that a "zero correction" must be added to all readings. To determine the amount of this correction, hold the balance in a horizontal position, tap it gently and note the position of the index. Estimate the fractions of a division in this and all other readings of the balance. Record this reading as the "Zero correction."

Certain statements made in the text (p. 44) are to be tested. These statements suggest several questions to which you are to secure answers.

A. How does the friction between two bodies depend upon the area of the surface in contact?

Weigh each of the toboggans and find the force required to pull each along the brass plate when loaded with approximately 1 kg. (the total weights must be the same for all loads). Unless the surface of the plate is exceptionally uniform, it will be best to make a mark on the plate at some convenient point and read the balance in each case just as the front of the toboggan passes this point. Several observations should be made with each toboggan and the results tabulated as follows:

METHOD OF TABULATING FRICTION DATA
Zero correction of balance—32 grams. Total load—1500 grams

Area of toboggan (sq. cm.)	Balance readings (grams)			Friction (corrected)
90	320	330	320	355
120	320	320	320	352
140	325	310	320	350
168	320	325	330	357

What answer does this table give to the question asked?

Proceed in a similar way to get answers to the following questions:

B. How does the friction between two surfaces depend upon the speed with which they slide over one another?

C. How does the friction between two bodies depend upon the force holding them together?

Tabulate your experimental results neatly and state clearly what answers are justified by the data. Compute the coefficient of friction for the materials used. Use all data obtained in the previous measurements and estimate the probable deviation of the average. This is computed in the same way as the probable *error* of a single observation (see Exercise 1) but is a measure, in part at least, of actual variations in the thing measured rather than of observational errors. If a 10-kg. weight were being pulled over a similar plate on one of these toboggans, how much might the measurements of friction be expected to vary?

Determine the coefficient of friction between the slider and the table top, the floor, etc. Also, find the coefficient of starting friction and compare it with that of kinetic friction.

Oil the plate and measure the friction when a rather heavily loaded slider is drawn over it. How does this compare with that which would be required for the same load if the surface were dry? Make your report a short essay on *friction* in which you use your data to illustrate important points.

Exercise 5

TO CALIBRATE AND USE A DIRECT-READING TORQUE METER

(Page 23)

Apparatus.—Cone of pulleys, spring balance, weights and paste. The object of the exercise is to become more familiar with the idea of a torque and its measurement.

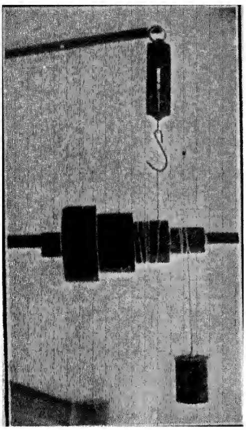


FIG. 8.—The turning effect of a force. When in use the balance is removed from the bar and raised or lowered at a uniform speed.

Arrange the apparatus as in Fig. 8, but attach the balance to a cord passing around the smallest pulley instead of the second. Paste a strip of paper over the scale of the balance, and mark the zero point. Hang a 100-g. weight on the opposite side of the same pulley (*i.e.*, string wound in the opposite direction) and mark the new position of the pointer. Measure the radius of the pulley and compute the torque corresponding to this position of the pointer. Do the same for loads of 200, 300, 400, and 500 g. As now calibrated, the balance will read torques directly as long as it is attached to the same pulley. Hang several weights from each of the other pulleys and read the torques directly from the balance. Measure the radii and compare the product *force* × *arm* with the torques as read.

Tabulate your results as below:

Observation	1	2	3	4	5	6
Force tending to cause rotation	—	—	—	—	—	—
Arm of force	—	—	—	—	—	—
Torque (computed)	—	—	—	—	—	—
Torque (as read)	—	—	—	—	—	—

Exercise 6

TORQUES DUE TO PARALLEL FORCES. CENTER OF GRAVITY

(Pages 58–63)

Apparatus.—Meter stick and supports, weights, thread, stand for index, irregular board with several holes bored in it, paper, thumb tacks, and plumb bob.

Put the knife-edge clamp on the meter stick and balance the latter carefully, adjusting the index near one end to mark the equilibrium position (Fig. 9). Read the position of the knife edge to $\frac{1}{10}$ mm. Hang a 100-g. weight in a loop of thread (or one of the special weights shown) at any convenient point on the left-hand end and balance it with a weight of different denomination on the right. Compare the torques. Repeat, using other weights and positions and then two or three weights at different positions on each side. What do your results show as to the condition of equilibrium? What is the per cent of error?

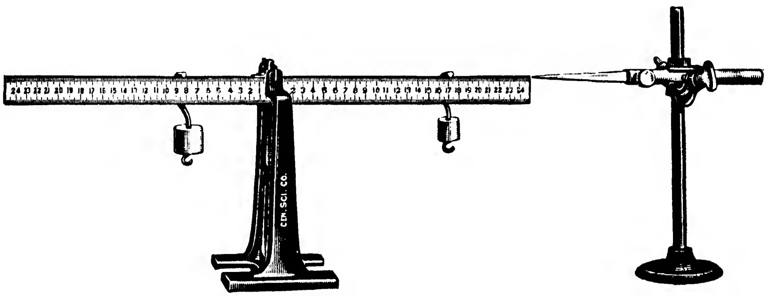


FIG. 9.—Meterstick, support and index.

Slide the meter stick through the knife-edge support until the latter is at the 35-cm. mark. What force causes the long end of the bar to fall when in this position? Where is this force applied? Place a 200-g. weight on the short end in such position as to bring the stick back to the horizontal. Compute the moment of this force and from this the weight of the stick. Repeat for another position of the knife edge. Weigh the stick and compare the weight as computed with that found from the moments.

Hang several weights from the stick and move the knife edge until the system is in equilibrium; *i.e.*, in the horizontal position. Where is the center of gravity of the system? Show by computation that the sum of the moments about this point is zero.

Tack a piece of paper to the irregular board and cut it off at the edges to the shape of the board, also punch holes in the paper corresponding to those in the board. Hang the board from the knife edge and mark the vertical line as determined by the plumb bob for each of three or four positions. Mark the center of gravity. How can you check this method of locating the

center of gravity? Tabulate all results and include the paper with your report.

Exercise 7

PRINCIPLE OF THE LEVER

(Page 28)

Apparatus.—Meter stick with a small hole in one end, index, weights, spring balance, pulley, support, thread, small rod.

A. Weigh the meter stick. Place the knife edge at the 20-cm. mark and balance the stick by a suitable weight hung at about the 5-cm. mark. Hang the spring balance from the support and attach it to the end of the meter stick by a thread passing around the pulley (Fig. 10) so that it pulls vertically down at the 95-cm. mark. Hang a 500-g. weight from the 10-cm. mark and raise the balance until the meter stick is horizontal. What is the

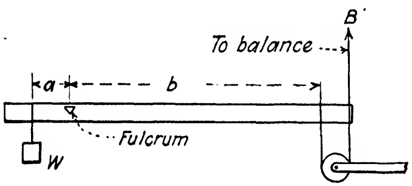


FIG. 10.

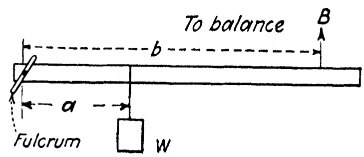


FIG. 11.

FIGS. 10 and 11.—Simple levers. The supports and balances are not shown.

reading of the balance? Show that this arrangement may be regarded as a lever of the first class. What is its mechanical advantage if the 500-g. weight is regarded as the *force applied* and the pull on the balance as the *force exerted* by the machine? How does this compare with the ratio of the length of the arms? Repeat for two other positions of the knife edges and applied forces.

B. Support the meter stick by thrusting the pin through the hole and resting the stick in the hook of the spring balance. Hang a 500-g. weight between these supports (Fig. 11). If one considers that the meter stick is being raised by the balance, to what type of lever is this arrangement equivalent? Check the measured mechanical advantage against the theoretical for several positions of the spring balance. Always bring the stick to the horizontal position before reading. In your report give a full discussion of the principle of the lever.

TABULATION OF DATA

	Weight			Balance pull			Mechanical advantage	
	Amount (W)	At	Arm (a)	Amount (B)	At	Arm (b)	W/B	b/a
A								
B								

Exercise 8

FORCE TABLE. VECTOR ADDITION

(Chapter VI and Appendix I)

Apparatus.—Force table, weights, pulleys, string, protractor, ruler, triangles.

The force table (Fig. 12) is a metal disk carrying a circular scale to facilitate the accurate measurement of the angles between the directions in which forces applied to a central disk or ring act. The procedure of the exercise is to set yourself a problem in the *composition of forces* (a special case of the *addition of vectors*), to solve this problem by the several methods (graphical and analytical) which are described in the text (Chap. VI), and to check the accuracy of your results by trial. The object sought is familiarity with the vector concept and with the simplest of vector problems.

Case 1. Two Forces.—Set two pulleys at any points on the force table and hang any convenient weights over them. Draw a circle about 10 cm. in diameter on a sheet of paper to represent the force table. Mark the zero and 180-deg. points and draw a diameter through them for use as a reference line. From the center of this circle draw two lines of indefinite length (greater than the radius of the circle) in the proper directions to represent the *lines of action* of the two forces.

Combine these forces by the graphical method so as to determine the magnitude and direction of the equilibrant. The

figure, when completed, will resemble Fig. 13 except that the actual magnitudes of the forces and angles should be given in place of the general symbols. Check the position and magnitude of the equilibrant by trial and record it on the same sheet. Is the experimental result in satisfactory accord with that found from the diagram? The sheet should be preserved and turned in as the full report on this part of the exercise. If more than one

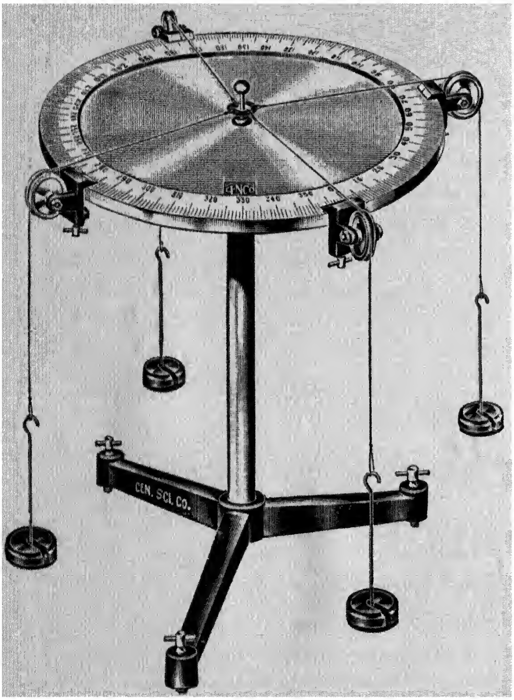


Fig. 12.—Force table.

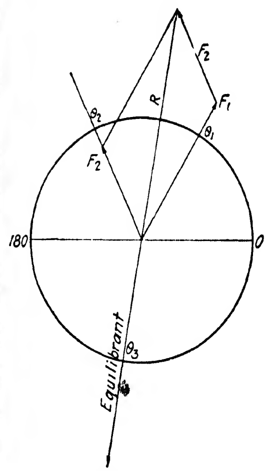


Fig. 13.—Method of preparing force diagram for Exercise 8.

person is working with the table at the same time, each should make his own diagrams.

Analytical Method.—On a second sheet of paper draw a circle as before except that the line at right angles to the previous reference line should also be drawn in to give the required pair of "rectangular axes." Call the 0- to 180-deg. line the X-axis and the 90- to 270-deg. line the Y-axis. Draw in the lines of action of the two forces as before and lay off the proper length on each. Project each of these vectors on the axes to find their X

and Y components. Mark each of the four components clearly on the diagram and compute the magnitude of each component from the relations

$$x_1 = F_1 \cos \Theta_1,\ y_1 = F_1 \sin \Theta_1,$$

etc. Compute the magnitude and direction of the resultant as described in the text (p. 53). How will the direction of the equilibrant be related to this? Compare this method with the graphical method as to accuracy and convenience.

Set up another problem using three forces instead of two and treat as before. If you have thoroughly mastered the subject of combining vectors this should take only a few minutes. If it goes slowly it is evidence that more work should be put on this subject and it will be best to set up and solve other problems until the procedure becomes familiar. You should be your own judge as to when it is time to stop. The diagrams properly marked and with such slight notes on each sheet as may seem necessary are the only report required for this exercise.

Exercise 9

THE COMPLETE CONDITIONS OF EQUILIBRIUM

Non-parallel Forces

(Chapter VII)

Apparatus.—Force table etc. as shown in Fig. 14, sharp pencil, paper, scissors, pin, drawing board, T square, triangle, dividers, thumb tacks, colored pencils, centimeter scale.

The essential part of this apparatus consists of an iron disk which "floats" on three balls in such a manner that it is completely free to move in the horizontal plane. The balls which rest on a second metal disk are kept in position by small wire rings and the upper disk is kept in position, when not in equilibrium, by a peg which passes through a hole in its center.

Taking Data.—Level the stand until the upper disk will remain in position without touching the central peg. Remove the upper disk to a table, cover it with a sheet of paper and fasten this in place by means of three of the small pegs, triming off any projecting portions. Also cut out the paper covering the

central hole. Attach a piece of stout thread about a foot long to each peg, replace the disk on the balls, attach the weight holders and place the threads over the pulleys. See that the height of the pulleys is so adjusted that each string lies in a horizontal plane.

Add weights (several hundred grams each) to two of the weight holders and determine by pulling on the third string the approxi-

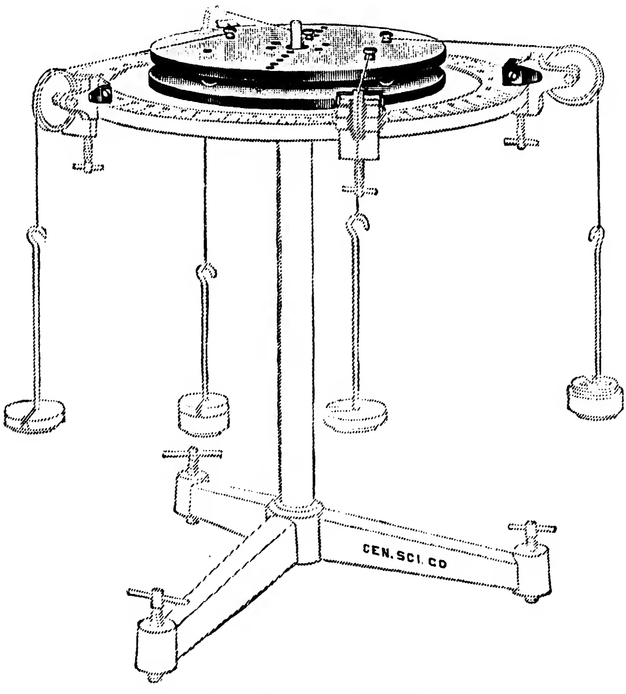


FIG. 14.—Apparatus for Exercise 9.

mate direction of the equilibrant of these two forces. Set the third pulley in this line. Adjust the weights on this pan (and if necessary the position of the pulley) until the disk "floats" without touching the central peg.

With a sharp pointed pencil make several dots under each thread. Be sure to look *straight down* on the thread when placing these dots and after the marks have been made check all around to see that they are exactly under the threads. Count the weights on each carrier (including the weight of the carrier

itself) and record along side each thread. This completes the taking of data for one set of forces.

Treatment of Data. A. Translational Equilibrium.—Remove the paper, lay it smoothly over a second sheet and fasten both to the drawing board. With a pin prick through each of the dots, thus transfering them to the lower paper: Remove the upper sheet and mark the numerical value of each force on the new sheet. With the aid of the triangle and your sharp pencil draw a fine line through each set of pin holes to mark the *lines of action* of the three forces.

Do these *lines of action* intersect at a point? Why is this a check of the accuracy of your work to this point?

Select any convenient point as an origin and by the aid of the T square and triangle draw a set of rectangular axes through the point, marking them properly. On each *line of action* lay off to scale a vector representing the force acting along that line. Project each vector on the X and Y axes by dropping perpendiculars upon the axes from each end of the vector. The T square and triangle will enable you to do this quickly and accurately, if you use a sharp pointed pencil and some care. Slipshod work or broad indefinite lines will lead to poor results. Mark the forces F_1, F_2, F_3 and the components X_1, Y_1, etc. and be sure that arrow heads are placed to show the sense of each component. If two components overlap it will be best to represent one of them by a parallel vector just above or below the axis. If colored pencils are available it will make the diagrams clearer if each force vector and its components are represented by a different color. (Don't try to do the original drawings and projections with the colored pencils.)

By means of the dividers lay off from the end of X_1, a length equal to X_2 and in the proper sense and add X_3 to this sum. Do the same for the Y components.

Is it true within a reasonable degree of accuracy that $\Sigma X = 0$ $\Sigma Y = 0$? Write a brief statement of your conclusion on the same sheet of paper which is to be submitted as your complete report on this part of the exercise.

B. Rotational Equilibrium.—Transfer the *lines of action* of the forces from the data sheet to another sheet of paper as before. Choose any point as a *center of moments* and drop a perpendicular from this point to each of the lines of action. Measure the length of each such *arm* and compute the magnitude of each

torque or *moment of force* giving due attention to sign. Mark the magnitude of each force beside its line of action and the length of each arm beside the proper line and color each force vector (drawn from the foot of the corresponding *arm*) and its arm some distinguishing color.

On the same sheet tabulate the values of forces, arms, and torques. Is it true that (with a reasonable degree of precision) $\Sigma T = 0$?

This sheet is the complete report for this portion of the experiment.

If time permits take another set of data using four forces and work it up in the same way.

Exercise 10

THE CONDITIONS OF EQUILIBRIUM

(Chapter VII)

Apparatus.—Light stick about 4 ft. along with screweye in one end and caster on the other, string, three spring balances, supports, weights.

Weigh the stick and determine the position of its center of gravity. Set the apparatus up as shown in Fig. 15, being careful to have the cords a and b horizontal and vertical, respectively. The balance B_1 rests on a block and is attached to a screweye in the wall, B_2 is supported by a cross-arm on an iron stand not shown in the diagram. Read balances B_1 and B_2 and measure F_1 with a third balance. (Do not forget to apply the required correction for use of balance in horizontal position.) Test the equilibrium conditions

$$\Sigma X = 0,\ \Sigma Y = 0,\ \Sigma T = 0.$$

Repeat with a 200-g. weight suspended from the screweye near the middle of the bar. Tabulate all results neatly.

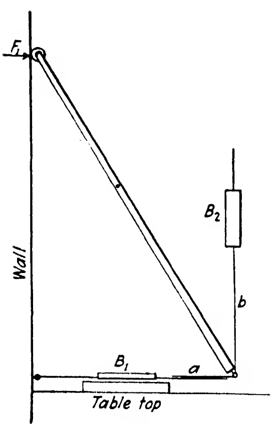


Fig. 15.—Diagram showing set up for Exercise 10.

If time permits, make a third set of observations with the balance supports so adjusted that the cords a and b are not horizontal and vertical. What additional data must be taken in this case?

GROUP III

SOME PROBLEMS IN THE STUDY OF MOTION

Exercise 11

A FREELY FALLING BODY

(Chapter IX)

Apparatus.—Free fall apparatus with electric timer and induction coil, glass plate and clamps, meter stick.

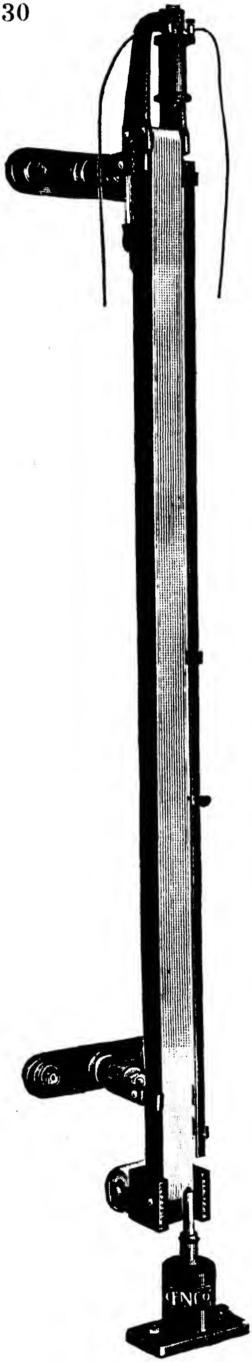
This exercise reproduces upon a laboratory scale the experiment upon the falling bomb described in the text (pp. 77–80). The essential requirement is that a heavy body fall under conditions such that it leaves a permanent record from which its position at the end of each of a number of equal time intervals may be determined. Because the timing device and the mechanism for releasing the weight involve electrical connections with which you are probably not familiar, the apparatus will be set up ready to operate by the instructor.

The apparatus is shown in Fig. 16. The body is held in position by an electromagnet and is dropped by breaking the electric circuit. Its positions are recorded upon a strip of specially prepared paper by an electric spark which passes through the falling body and the paper on its way from one part of the frame to another.

Familiarize yourself with the operation of the apparatus before beginning to make observations. Notice in particular how the length of the time intervals is controlled. *Do not touch the frame while the timing apparatus is in operation.* There is no danger in doing so, but most people dislike electric shocks.

To find the period of vibrations, stop the indicator by pressing on the key and read both dials. Release the key as the second hand of your watch passes the zero mark and allow the indicator to run for exactly 2 min.

Again read both dials and determine the number of sparks that pass per second and hence the time interval Δt between



successive sparks. Repeat until you are sure that this interval is known with an accuracy of a few parts in a thousand. Why is such accuracy needed?

After determining the period as above, you are ready to allow the falling body to make its record. Disconnect both switches and place a fresh strip of the sensitized paper in position. Close the switch operating the electromagnet and hang the weight from the magnet. Close the timing circuit and, if necessary, tap the vibrator to set it in motion. Open the switch in the circuit of the magnet and then the one in the timing circuit. The paper should show a half dozen conspicuous dots where sparks have passed, and a more careful examination will show a tiny pinhole near the center of each dot.

Tear off the paper used and clamp it to the glass plate which should be set up at an angle with a lamp or white paper behind it so that the pinholes are easily seen. These are best marked with a short cross line at right angles to the line of fall, using a very sharp pencil. Lay a meter stick along the line of fall, placing the 1-cm. mark exactly upon the *second* pinhole, and read off the positions of the successive marks estimating tenths of millimeters with care. (Why not start with the first pinhole instead of with the second?)

Using the period of the vibrator Δt as a unit of time, make a table which shows the actual meter-stick readings R, the distance fallen after the body passed the mark used as a starting point s, the distance fallen during each interval $\frac{\Delta s}{\Delta t} = \bar{v}$, and the rate at which the velocity $\bar{v}$ changed $\frac{\Delta v}{\Delta t} = a$.

FIG. 16.—Apparatus for measuring the acceleration of a freely falling body.

Does the acceleration appear to be constant within reasonable limits of error? In what units are velocities and accelerations expressed in this table? Find the average value of the acceleration in centimeters per second.

FIG. 16*a*.—Electric vibrator for measuring small intervals of time.

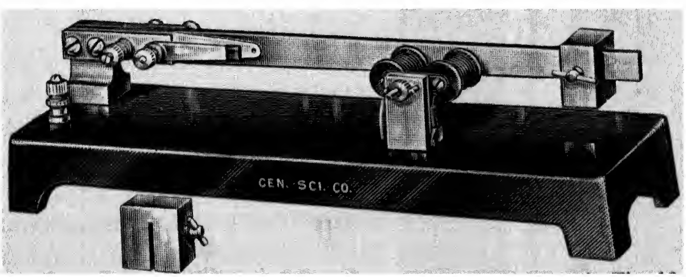


FIG. 16*b*.—Recording device operated by the vibrator shown in Fig. 16*a*.

Take two more records and treat as above. Work carefully but rapidly. After the first set has been taken, the entire time occupied in obtaining a record, making measurements and computing results ought not to require more than 15 min.

Your report should be a short essay upon the subject of uniformly accelerated motion, using your data as illustrative material. In particular compute the time of fall to the point where you began to make measurements and the velocity at the instant the last spark passed. Is there any particular advantage

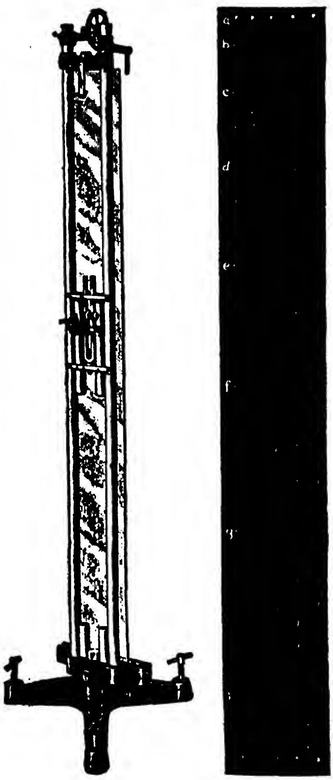
in reading positions as directed rather than measuring the distance fallen in each interval separately?

Exercise 12

THE PRODUCTION OF MOTION

(Chapter X)

Apparatus.—Falling-fork apparatus as illustrated (Fig. 17), meter stick, supports for glass plate, suspension of cornstarch in wood alcohol, spray pump,[1] weights, small T square.



(a) (b)

FIG. 17.—Falling fork and typical curves.

Prepare one of the glass plates by spraying it with the cornstarch suspension. Shake or stir the suspension thoroughly before using and spray it on as rapidly as possible. It is desirable to get an even, light coating and no retouching can be done. Best results are obtained with the plate standing nearly vertically and using a fairly thick suspension.

Record the weight of the fork and hang a can which with its contents weighs about 30 g. (or whatever may be directed for this particular apparatus) less than this over the pulley. (The 30 g. difference in weight is to correct approximately for the frictional resistance during fall.) Note the frequency of the fork. Clamp the fork to the top of the guides; set it in vibration; place the plate in position and see that the stylus attached to the fork just touches the plate. Release the fork and give it a fairly sharp downward push. If the 30 g. difference in weight exactly compensates for the frictional resistance, the fork will fall at a

[1] The metal atomizers sold for use with insecticides are cheap and efficient.

uniform rate and the waves traced by the tuning fork will be of the same length near the bottom as near the top. If this condition is not fairly well fulfilled, readjust the balancing weights and repeat.

Remove 200 g. from the can, raise the fork, and obtain two traces with this driving force. Repeat, removing 200 or 300 g. at each step, until five trials have been made, the last being with the fork wholly unbalanced.

Take the plate to your table and support it at an angle of about 45 deg. with white paper behind so as to make the markings clearly visible. With a *very* sharp pencil mark off the curves into groups corresponding to ⅛ sec. in those having the smaller accelerations and $\frac{1}{16}$ sec. in the others. These marks must be carefully placed at the crest of the waves and at right angles to the length of the trace and may conveniently be marked with the wave number as, 16–32–48–etc. *Be careful not to erase one curve while working on another and preserve all curves until your data and calculations are complete and have been checked by the instructor.*

When the first curve has been counted and marked off, place a meter stick on edge with the 1-cm. mark on the 0 of the waves and read off the *position* of each later mark. Tabulate as shown.

Wave	Reading, $(s+1)$	Δs, cm.	$\frac{\Delta s}{\Delta t} = \bar{v}$, cm./sec.	$\Delta \bar{v}$	$\frac{\Delta \bar{v}}{\Delta t} = a$, cm./sec.^{2}
0	1.00	______	______	______	______
16	______	______	______	______	______
32	______	______	______	______	______
48	______	______	______	______	______
64	______	______	______	______	______
96	______	______	______	______	______
128	______	______	______	______	______

As soon as the readings are completed, one student should proceed to count the next curve while the second performs the computations necessary to find the acceleration in this case. The observers should alternate in counting and computing. Make the records for each weight in the can on a separate sheet and have all computations for each curve completed before reading the next.

The column headed Δs is obtained by subtracting each *reading* from the one following. The reading less one gives the whole distance s fallen from the arbitrarily chosen zero level, so that the values Δs are the distances fallen in each successive time interval. The average velocity $\bar{v}$ during each interval Δt is $\Delta s/\Delta t$ and the differences between successive values of $\bar{v}$ are the changes in velocity ($\Delta\bar{v}$) which take place in the interval Δt so that the average acceleration during each interval is $\frac{\Delta\bar{v}}{\Delta t} = a$. Finally, find the mean value of the acceleration and compute F/Ma.

An inspection of the table shows that the same result may be reached with less computation if one subtracts the successive values of Δs and divides the mean value of these *second differences* ($\Delta(\Delta s)$) by $\overline{\Delta t^2}$. This is equivalent to working with the chosen time interval as a unit until the end of the operation and then converting the acceleration in centimeters per (interval)^2 into centimeters per second^2 by a single operation. Do your results tend to confirm the statement that F/Ma is a constant?

Exercise 12a

THE PRODUCTION OF MOTION, ALTERNATIVE METHOD

(Chapter X)

Apparatus.—Car and track, sensitized paper, electric timer, slotted weights (two 500 g., two 200 g., one 100 g.), meter stick, glass plate, and clamps.

The timing device is the same as that used in Exercise 11 and will be set up and connected to the apparatus by the instructor. Its period must be determined as directed in Exercise 11.

Place the weights on the carrier as shown in Fig. 18. Draw the car to the back end of the track and attach a strip of paper just long enough to allow the clamp to hang free from the roller. Adjust the leveling screws until the weight of the clamp is just sufficient to keep the car moving at a uniform speed. See that the spark tube is set near one edge of the paper. Attach the weight carrier, draw the car to the back end of the track, and release it after starting the timer. Move the spark tube so that the traces will not overlap, transfer 100 g. from the car to the weight carrier, remove the carrier, and again adjust for friction; replace the carrier and make another record. Repeat this

process until the weights are all on the carrier. Remove the paper, measure each record, and compute the acceleration for each in centimeters per second squared as was done in Exercise 11. Notice that in this case the mass set in motion has remained constant while the force causing acceleration has varied. Plot a curve using forces as abscissæ and accelerations as ordinates. What does this show? For each case find the value of the ratio F/ma. Is it a constant within reasonable experimental limits?

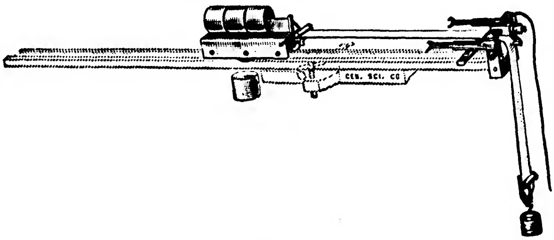


Fig. 18.

Devise a method by means of which a constant force can be applied to different masses, take several records (correcting for friction in each case) and compute the accelerations as before. What do these results show? Be sure to give an adequate justification of your answer from the data. Express the accelerating force in dynes and compare with the product ma in each case.

Make your report a short essay on *Newton's Second Law of Motion* using your data as illustrative material.

Exercise 13

THE CONSERVATION OF MOMENTUM

(Pages 93–95)

Apparatus.—Ballistic pendulum, carbon paper, meter stick, plumb line, steel scale.

Ballistics is defined as the science of projectiles and the ballistic pendulum is so called from its application to the measurement of the velocities of projectiles. In the present exercise we shall measure the velocity v_b of a ball fired from the spring gun by means of the ballistic pendulum, and also by applying the laws of falling bodies, and compare the two results. The exercise therefore supplies a very complete review of the whole subject of accelerated motion and Newton's laws of motion.

Examine the apparatus, level it carefully, and try a few experimental shots to be sure everything is working properly and that you understand the manipulation. Fire the ball into the pendulum ten times, recording the notch at which the pendulum stops in each case, and take the mean. With the steel scale measure the height from the top of the base to the center of gravity of the pendulum when it hangs at rest and also when the

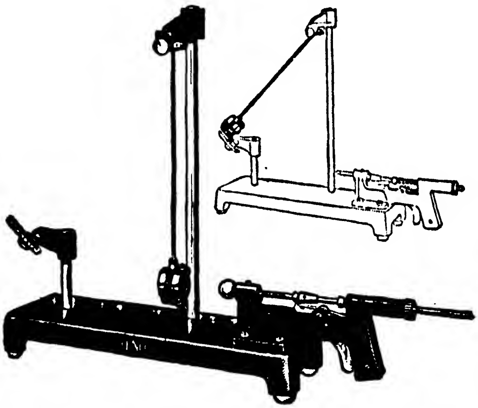


FIG. 19.—Spring gun and ballistic pendulum.

catch is in the proper notch. (The center of gravity is at the tip of the indicator attached to the bob.) Be sure that the scale is accurately vertical, estimate tenths of millimeters and repeat several times. The difference is the height of rise h of the pendulum. The velocity v_p with which the pendulum started to move must have been $v_p = \sqrt{2gh}$, and the momentum M_2 of the combined pendulum and ball (momentum after impact)

$$M_2 = v_p(m_b + m_p) = (m_b + m_p)\sqrt{2gh}.$$

This must, from the law of conservation of momentum be equal to the momentum of the ball alone before the impact; *i.e.*,

$$M_1 = m_b v_b = M_2 = (m_b + m_p)\sqrt{2gh};$$

hence,

$$v_b = \sqrt{2gh}\left(\frac{m_p + m_b}{m_b}\right).$$

In the second part of the experiment the pendulum is removed, the horizontal distance which the projectile travels while falling to the floor measured, and the initial velocity of the ball com-

puted from the laws of falling bodies. Set the apparatus near one corner of a table, level carefully, and try an experimental shot to locate the approximate range. Drop a plumb line from the position of discharge marking its intersection with the floor and measure the height from the floor to the center of the ball. Put a sheet of carbon paper between two sheets of white paper and put the whole down so that the spot at which the experimental shot struck is near the center of the sheet, adding weights to hold the paper in position. Measure the distance from the plumb line to the nearer edge of the paper carefully. Fire the spring gun several (five to ten) times being careful that its position on the table remains unchanged. Each shot should strike the paper and leave its record in the form of a spot under the carbon paper. Measure the distances from the nearer edge of the paper to the center of each spot, average and add to the distance from plumb line to paper to find the range R of the gun at this height h from the floor. From the equations for the motion of a projectile, $R = V_h t$ and $h = \frac{1}{2}gt^2$ show that when discharged horizontally, as in this case, the initial velocity is given by

$$V = R\sqrt{\frac{g}{2h}}.$$

Compare with the result obtained from the momentum experiment.

Notice that the kinetic energy *decreased* as a result of the impact. Compute values of kinetic energy before and after impact and compare the ratios.

$$\frac{\text{Kinetic energy after impact}}{\text{Kinetic energy before impact}} \text{ and } \frac{m_b}{m_b + m_p}$$

Can you show by eliminating the velocities from the equations for kinetic energy that these two ratios should be equal?

Exercise 14

UNIFORM CIRCULAR MOTION

Conical Pendulum

(Pages 98–100)

Apparatus.—Can suspended from ceiling, weights, meter stick, stop watch, string, chalk.

Hang the can loaded with about 2 kg. so that it clears the floor by 2 or 3 in. when at rest, and mark the point directly under it. With this point as a center, describe two circles having radii of about 1.5 and 3 ft. Set the can swinging in a circular path so that it is as nearly as possible over the inner circle and determine the period with considerable care. Do the same with the can swinging over the outer circle. Double the weight in the can and repeat. Tabulate all observations neatly. Does the period of this "conical pendulum" depend upon the mass of the moving body? Can you explain why? Does the period depend upon the radius of the circle in which the body moves?

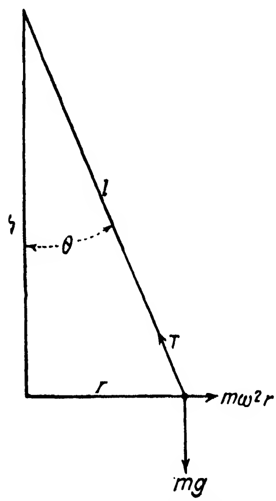


FIG. 20.—Forces acting on conical pendulum.

Consider the forces which act upon the weight when moving steadily in a circle of radius r (Fig. 20). From the vector relations

$$\frac{mr\omega^2}{mg} = \tan \Theta = \frac{r}{h} = \frac{r}{l \cos \Theta},$$

and since

$$\omega = \frac{2\pi}{T},$$

this may be written (after cancellation and simplification) in the form

$$T = 2\pi\sqrt{\frac{l \cos \Theta}{g}}$$

or

$$g = \frac{4\pi^2 l \cos \Theta}{T^2}.$$

Compute the value of Θ from your observations and solve for the value of the acceleration due to gravity. What are the greatest sources of error? What would be the length of a simple pendulum which would vibrate with the same period as a given conical pendulum?

Exercise 15

UNIFORMLY ACCELERATED MOTION OF ROTATION

(Pages 101–105)

Apparatus.—Heavy disk mounted on ball bearings (Fig. 21), pulley, weights, string, stop watch, meter stick, support.

This exercise affords an extensive review of many simple relations. Be sure that you understand clearly what you are doing at each step.

Attach a string to the peg on the rotating disk and pass it over a pulley which is at least 2 meters from the floor. Attach a 200-g. weight and make the length of the string such that this weight will just touch the floor when the string is completely unwound. Raise the weight by winding the string on the drum, note its height h and with a stop watch determine the time required for it to fall to the floor. Also note the height h_1 to which the weight is lifted as the string winds up again on the drum. Check several times and also use different weights.

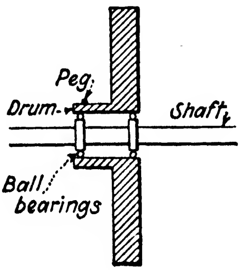


FIG. 21.—Section through disk used in Exercise 15.

Since the weight fell from a height h and returned to a height h_1, there was a loss of energy during the operation amounting to $mg(h - h_1)$ ergs. A part of this loss was due to loss of the kinetic energy which the falling weight possessed at the instant it struck the floor. This amounted to $\frac{1}{2}mv^2$ ergs where v is the velocity at the instant of impact. Since the motion is uniformly accelerated this is twice the average velocity $\bar{v}$ during the fall which is determined from the observations. The work done against friction accounts for the remainder of this lost energy and is

$$w = mg(h - h_1) - \tfrac{1}{2}mv^2 = f(h + h_1).$$

Or, since $v = 2\bar{v} = \dfrac{2h}{t}$,

$$f = \frac{mg(h - h_1) - 2m\bar{v}^2}{h + h_1} = \frac{mg}{h + h_1}\left(h - h_1 - \frac{h^2}{gt^2}\right)$$

where f is the average equivalent frictional resistance; *i.e.*, the correction to be applied to the weight mg to find the effective force causing motion. This effective force $(mg - f)$ is in part used to accelerate the falling weight and in part to set the wheel in motion. The part used to accelerate the falling weight is

$$f' = ma = \frac{mv}{t} = \frac{2m\bar{v}}{t} = \frac{2mh}{t^2}.$$

Allowing for this and for the friction, the effective force applied to the drum to cause rotational acceleration is

$$F = mg - (f' + f).$$

The torque $T = Fr$ where r is the radius of the drum.

By definition the moment of inertia I of the disk is

$$I = \frac{T}{\alpha}.$$

If the radius of the drum is r and the linear acceleration of the falling weight a, the angular acceleration α may be found from the relation

$$\alpha = \frac{a}{r} = \frac{2h}{t^2 r}.$$

Compute the value of I from the average of each set of your observations.

It may be shown by use of the calculus that the moment of inertia of a thick ring such as is here used is

$$I = \tfrac{1}{2}M(R_1^2 + R_2^2)$$

where M is the mass of the body, R_1 and R_2 the inner and outer radii of the ring. The mass M is marked on the disk and the radii may be measured. Compute I by this method and compare with the average of the values previously obtained.

GROUP IV

HEAT AS A MEASURABLE QUANTITY

(Chapters XII and XIII)

The beginnings of accurate knowledge as to the nature of heat date from the experiments of Dr. Black, of Edinburgh, which placed heat in the list of measurable quantities. The group of exercises which follow are all directed to the end of acquainting you with some of the important phenomena of heat which are essentially quantitative in character. The simplest method of measuring heat quantities is based upon the assumption that heat is passed from one body to another without loss. This is known as the "method of mixtures." Since the materials used must always be contained in vessels which themselves take part in the heat exchanges, it is first necessary to determine the heat capacity of the calorimeter and its accessories.

Exercise 16

METHOD OF MIXTURES

(Chapter XII)

Apparatus.—Calorimeter, heater, stirrer, balance, weights, thermometers (0 to 100 in 1°), reservoir, brass tube, medicine dropper, one thermometer (0 to 50 in $\frac{1}{5}$°), lead shot, clippings of copper, iron, aluminum.

A. The Heat Capacity of a Vessel.—Weigh the inner vessel of the calorimeter with the brass tube and stirrer in it, add the thermometer and weigh again. While it is still on the pan of the balance add exactly 200 g. of water using the dropper to make the final balance. Replace this vessel in the outer vessel which serves to protect it from drafts. Attach a short length of rubber tubing to the lower opening on the heater. Fill with water and heat to about 70°C. If two are working on the exercise, one should do this while the other is weighing out the cold water. Determine the temperature of the water in the calorimeter and that of the hot water, *keeping both well stirred.* Place the calorimeter near the heater and connect the brass tube to the lower outlet of the

heater. Tilt the heater enough to let a volume of water nearly equal to that already in the calorimeter flow from the reservoir. Disconnect, stir thoroughly and read the thermometer in the calorimeter as quickly as it becomes constant. Weigh the inner vessel and thus determine the exact quantity of hot water added. Tabulate all observations and make computations as indicated.

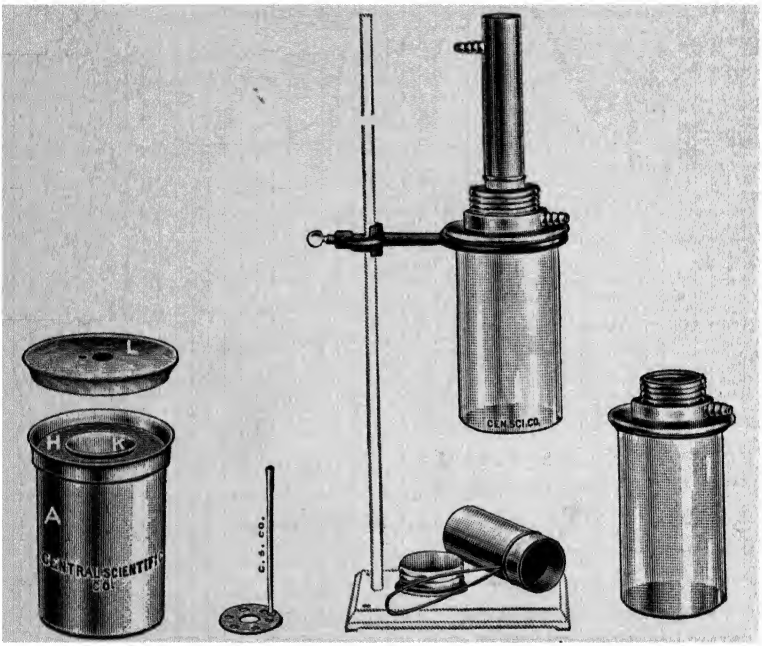


Fig. 22.—Calorimeter and heater for Exercise 16.

Method of Tabulating Observations and Computations

Temperature of hot water.........., cold water.........., mixture......

Change in temperature of hot water.........., of cold water..........

Weight of hot water.........., of cold water..........

Heat lost by hot water..........

Heat gained by cold water..........

Heat taken up by calorimeter..........

Temperature change of calorimeter..........

Heat capacity of calorimeter..........

Be sure that the reason for each calculation is understood. Repeat the determination but with warm water (50°) in the calorimeter and cold added from the reservoir and tabulate as before. Compare the values of the *heat capacity* of the calori-

meter, that is, the quantity of heat required to raise the temperature of the calorimeter by 1° as determined by these two trials. (The tube and thermometer are included in this.) Why is this sometimes called the water equivalent of the calorimeter? Do you see any reason for reversing the *hot* and *cold* in the second trial?

If a reservoir or heater of the type shown is not available, the water may be poured directly from a beaker into the calorimeter. In this case there will be considerable loss of heat if the warm water is above 50°C.

Specific Heat of a Substance. Method of Mixtures.—Weigh the calorimeter and stirrer empty and dry and also with the accurate thermometer in it. Add 200 g. of water at about room temperature and determine the temperature as exactly as possible. Pour in quickly a quantity of lead shot which have been heated to about 100° in a vessel on a steam bath. The temperature of the shot must be determined by a thermometer with the bulb well buried in the shot and must remain constant for at least 3 min. before the transfer. The top of the vessel in which the shot are heated is best closed with a plug of cotton, otherwise one cannot be sure that the temperature is uniform throughout the whole mass. As this heating of the shot takes considerable time, it should be begun at the outset of the exercise unless a common heater is used by all the students, in which case, the instructor will see that hot metals are ready for use. Weigh the calorimeter and contents and determine the weight of lead added. Tabulate as in *A*. Compute the quantity of heat added and set up an equation in the form

Heat added to calorimeter and water = heat lost by shot. Letting W be the mass of the water, w the water equivalent of the calorimeter etc., M the mass of the shot, s the specific heat of lead, T_1 the temperature of the cold water, T_2 that of the shot, and T_3 that of the mixture, put this statement into algebraic form and compute the specific heat of the lead. Repeat for two other metals. Compare your values with those given in the "Handbook." Define carefully the terms *heat capacity of a body* and *specific heat of a substance.*

In this experiment no allowance has been made for the fact that there is likely to be some loss of heat from the calorimeter between the time the shot are added and that at which the temperature of the mixture is read. In more exact work due allowance for

this must be made. The methods of such radiation corrections will be explained in another place. If possible, repeat the observations to enable you to get some idea as to the degree of reliability of your results.

Exercise 17

LOSS OF HEAT BY RADIATION

Cooling Curves for Bodies Which Do Not Undergo Change of State

(Pages 128, 586–588)

Every body is constantly exchanging heat with its neighbors. If the body is warmer than its surroundings, it loses heat, if cooler it gains heat. The laws governing this process of *radiation* are very important and some of the simplest of the results are easily illustrated.

Apparatus.—Water-jacketed can about 4 in. in diameter and of equal height with wooden cover to which three small brass containers may be attached.[1]
Two of these are blackened while the third has a polished surface. Holes in the cover allow thermometers to be inserted in the vessels. Trip balance, weights, kerosene, or any other convenient non-volatile liquid, three thermometers (0 to 100° in 1°).

Weigh the containers and calculate the heat capacity of each.

Fill the polished container and one of the blackened ones with water to any convenient depth, adjusting the amount of water in each so that the heat capacities of the two are equal. Fill the third container with kerosene to approximately the same depth and weigh. Heat all three to a temperature of between 60 and 70°, attach to the cover and place in the water-jacketed protecting vessel. Turn the thermometers into positions where their graduations are easily seen and read each thermometer at 1-min. intervals estimating fractions of degrees.

In making these readings, one observer should read the thermometers while the other keeps time and records readings. The

[1] If such a container is not available, three ordinary jacketed calorimeters may be used. In this case, satisfactory inner tubes may be made from pieces of light-walled brass tubing ¾ in. in diameter and about 2 in. long by soldering a disk of sheet brass over one end and attaching this tube to the thermometer by a tight-fitting rubber stopper.

procedure consists of reading one thermometer each 20 sec. For example, the thermometer in the bright, water vessel may be read on the even minute, that in the black, water vessel on the 20-sec. mark, etc. To insure making the readings at the right time, the recorder should give some preliminary signal about 5 sec. before the reading is to be made. For example, if the containers are numbered as 1, 2, 3, the recorder says "*ready, one . . . read.*" Naming the thermometer to be read will serve to avoid mistakes on the part of the observer. Record the temperature of the water in the jacket at the outset and at the end of the observations. Continue observations for about 20 min.

At once plot a curve for each vessel, using times as abscissæ and temperatures as ordinates. (It will save time if the curve sheets are prepared beforehand and the observations plotted as read.) What do these curves show as to the comparative rates of cooling in the three cases? How can you account for these differences?

If one assumes that the *rate of loss of heat* (*not rate of fall of temperature*) depends only upon the character and extent of the heated surface and the temperature difference between the hot body and its surroundings, it follows that for the two blackened vessels the heat losses in falling from one temperature to another are directly proportional to the times required for the temperature change. Draw two horizontal lines (lines of equal temperature) and read off from the graphs the time required for the water in the blackened vessel to cool through this temperature range and also that for the kerosene. We then have the following relations from which the specific heat of the kerosene may be computed. (Quantities with subscript w refer to water, with subscript k to kerosene. C_v and C_v' are the heat capacities of the two vessels and m and m' the masses of the water and kerosene, ΔT the fall in temperature, Δt_w and Δt_k the time intervals for equal temperature changes.)

$$\frac{\Delta H_k}{\Delta H_w} = \frac{\Delta t_k}{\Delta t_w};$$

hence,

$$\Delta H_k = \frac{\Delta t_k}{\Delta t_w} \cdot \Delta H_w = \frac{\Delta t_k}{\Delta t_w}(C_v + m)\Delta T,$$

and also,

$$\Delta H_k = (C_v' + S_k m')\Delta T.$$

Equate these two values of ΔH_k and determine the specific heat (S_k) of kerosene. Compare with tabular values.

Newton's Law of Cooling.—From the curves determine the average rate of fall of temperature during each 2-min. interval and tabulate. Plot a curve using these values of $\Delta T/\Delta t$ as ordinates and the differences in temperature between the radiating body and the water jacket (at the middle of each time interval) as abscissæ. Does this curve justify the statement that: *For small differences of temperature the rate at which a body cools is approximately proportional to the temperature difference between that body and its surroundings?*

Exercise 18

COOLING THROUGH CHANGE OF STATE

A STUDY OF HEAT PHENOMENA WHICH ACCOMPANY SOLIDIFICATION. CRYSTALLINE AND AMORPHOUS SUBSTANCES

(Pages 139–140)

Apparatus.—Test tubes of paraffine, beeswax, and salol each with a (0 to 100° in 1°) thermometer and stirrer mounted in the cork, supports, beaker stand with wire gauze, and Bunsen burner.

Melt the materials in the test tubes by placing the tubes in a beaker of hot water. Be sure that all are completely molten but avoid heating far above the melting points since this will unnecessarily prolong the time of readings. About 10° above the melting point of each substance is sufficient. Support the test tubes in a place free from draughts and take temperature readings of each at 1-min. intervals until all are solidified.

These readings should be taken as directed in the previous exercise (one thermometer being read each 20 sec.) and if a sheet of coordinate paper has been prepared, the recorder will have ample time to plot the temperature-time curves as the readings are taken so that the progress of the cooling can be watched on the graph. Twenty minutes should, in general, be long enough for the observations to continue but they must be kept up for a short time after all materials are solid. Explain clearly the heat changes which took place during each stage of the cooling in the three cases. What marked difference between the salol curve and the other two? What is the *melting point* of salol? What about the melting points of paraffine and beeswax?

From the slope of the cooling curve for liquid salol at the solidification temperature determine the approximate rate of fall of temperature under these conditions. What can you say as to the rate at which heat is liberated during the process of solidification? Why did this process go on so slowly? Can you suggest a method by which the heat given out by the salol during solidification might be computed from these observations? Can you think of any reason why such a determination of the "heat of solidification" might not be very accurate?

Exercise 19

HEAT OF VAPORIZATION OF WATER

A Further Study of the Heat Changes Which Take Place during Change of State

(Page 122)

Apparatus.—Boiler, condenser, calorimeter, steam trap, thermometer 0 to 50 in $\frac{1}{10}°$, balances, and weights.

The problem is to determine accurately the quantity of heat liberated by the condensation of 1 *g. of steam at the boiling point.* This quantity is called the "*heat of vaporization*" of water. The method consists in the accurate measurement of the amount of water condensed, and the determination of the amount of heat added to the calorimeter and its contents. Some precautions and refinements of experimental methods beyond those previously used are essential if satisfactory results are to be obtained.

The most critical part of any accurate heat measurement lies in the determination of the correction which must be made for loss of heat by radiation during the time of operation. We shall therefore give some consideration to the general methods for doing this.

The measures to be adopted fall into two classes, prevention and correction. Radiation losses may be minimized by using well-insulated vessels, by keeping the temperature difference between the system and that of its surroundings as small as possible, by shortening the time during which radiation takes place, and by so arranging matters that gain of heat during one part of the operation may offset loss during another. If the latter adjustment were perfect, no *correction* would be necessary.

Radiation *corrections* depend upon a knowledge of the *temperature* and *rate of change of temperature* throughout the progress of the experiment. Any heat measurement divides itself into three periods:

a. The preliminary period in which one determines the initial conditions as to *temperature* and *rate of change of temperature.*

b. The period of heat exchanges during which regular observations of the *temperature* are made and recorded.

c. The final period in which the *temperature* and *rate of change of temperature* under the final conditions are determined.

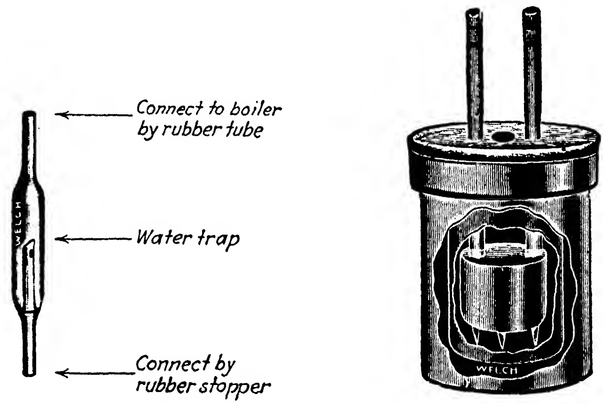


FIG. 23.—Steam calorimeter and water trap for Ex. 19. Steam is supplied from a heater like that used in Ex. 16 which is connected to the steam trap by rubber tubing. The trap is best connected to the condenser by means of a rubber stopper which fits over the outside of each by half its length. It is best to wrap the trap rather thickly with cotton or other insulating material both to prevent loss of heat and to make handling safer. Just before completing the connection lift the trap so that all condensed steam in it and in the rubber tube may run back into the boiler.

Weigh the condenser empty and dry to an accuracy of 0.01 g. In order to ensure the dryness it is best to rinse the condenser, both within and without, with a small quantity of wood alcohol and dry it by drawing a stream of air through it for 2 or 3 min.

Compute the heat capacity of the calorimetric system. This consists of the calorimeter, condenser, stirrer, water, and thermometer. The heat capacity of the thermometer (which is partly glass and partly mercury) cannot be computed in the usual way, but may be easily found from the fact that the *heat capacity of a cubic centimeter* of glass is nearly equal to the heat capacity of an equal volume of mercury. In short, the heat

capacity of the portion of the thermometer which is immersed in the water is equal to that which would be possessed by an *equal volume* of mercury. Before weighing the water in the calorimeter note the approximate length of the thermometer immersed and determine its volume by immersing it to the same depth in a small graduate. Do not remove the thermometer from the calorimeter after the latter has been weighed since to do so is likely to result in the loss of an appreciable amount of water.

Set up the calorimeter (Fig. 23) but leave the steam line disconnected. Start the boiler and adjust the flame so that the steam issues from the steam trap at a moderately rapid rate. Keep the water in the calorimeter well stirred and carry out the observations of the preliminary period. (It is desirable that water some 10° below room temperature be used.) Take five readings at 1-min. intervals and record in such a way as to show both *temperature* and *rate of change of temperature.* Immediately, after making the last reading of the preliminary period, connect the steam line to the condenser and close the other outlet to the boiler.

Read the thermometer each half minute until the temperature is approximately 10° above that of the room. Disconnect the boiler but continue to stir the water and to read the thermometer each half minute until the data needed for the final period has been obtained. All thermometer readings except those taken during the period of heat exchange should be estimated to fractions of the smallest scale division. Note the room temperature and the barometric height. Remove the condenser, dry (outside) with alcohol, and weigh.

Calculating the Radiation Correction.—An approximate correction which is often sufficiently exact may be found by multiplying the mean of the initial and final rates of change of temperature by the time required for the heat exchange. A more exact correction may be found by plotting the observed and corrected time-temperature curves as in Fig. 24. In this graph, curve I is plotted directly from the readings, while in curve II, the proper correction has been added to each observed reading so that this curve is assumed to represent the way in which the temperature would have changed if there had been no radiation. The corrections are found as follows:

In Fig. 25, *rates of change of temperature* due to radiation are represented as a function of *temperature.* The points A and B which correspond to the average rates during the preliminary

and final periods are located and joined by a straight line. The point of this curve corresponding to room temperature is located and the line of zero rate of radiation drawn through this point. The rate of radiation at any temperature is given by the ordinate of the corresponding point on the line AB. (Notice that this is an application of Newton's law of cooling.) Set down in

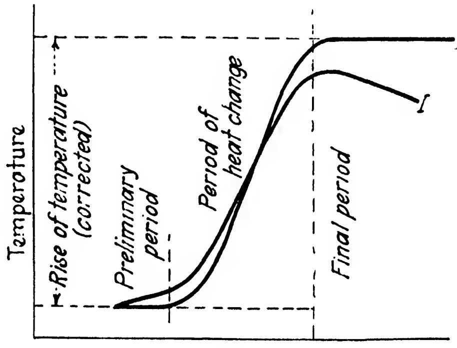


FIG. 24.

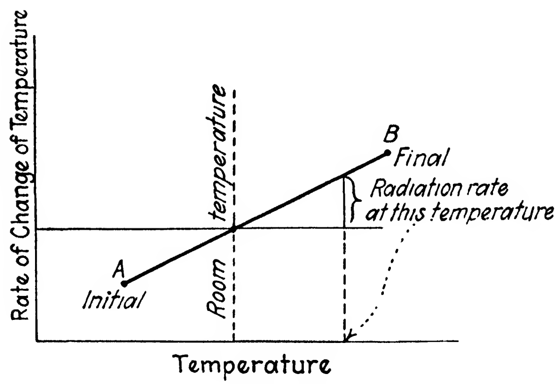


FIG. 25.

FIGS. 24 and 25.—Curves to illustrate method of making radiation corrections.

your table of data opposite each reading taken on the full minute the corresponding *rate of radiation* as read from this curve. Use the temperature read at the previous half minute as the mean temperature during that interval. (Do not forget to give each value its proper sign.) The correction to be applied to any reading is the algebraic sum of all the radiations up to that point. Tabulate these values in the next column and finally add a

column in which the correction has been added to (or subtracted from) the temperature as read.

The whole set of observations and corrections should be tabulated under the following headings:

Time of reading. (t)
Temperature as read. (T)
Mean temperature during each reading interval. (T_m)
Radiation rate $\left(\frac{\Delta T}{\Delta t}\right)$ corresponding to mean temperature. From Fig. 25.
Correction; *i.e.* total radiation loss. $\left[\Sigma\left(\frac{\Delta T}{\Delta t}\right)\Delta t = \Sigma\Delta T\right]$
Corrected temperature. ($T_c = T + \Sigma\Delta T$)

If the corrections have been accurately made, it is evident that the lines representing the initial and final periods should be horizontal and the *rise of temperature* may be determined with accuracy. Make up a balance sheet for the heat account as follows.

Rise of temperature (corrected)........................
Weight of calorimeter........................
Weight of condenser........................
Weight of stirrer........................
Total brass........................
Specific heat of brass........................
Water equivalent of brass parts........................
Volume of thermometer........................
Water equivalent of thermometer........................
Quantity of water in calorimeter........................
Heat capacity of calorimeter system........................
Heat taken up by calorimeter system........................
Water condensed........................
Boiling point (from barometric reading and Handbook)........
Heat given up by cooling water........................
Balance (heat supplied by condensation)........................
Heat of condensation........................

Exercise 20

THE HEAT OF FUSION OF ICE

(Page 123)

Apparatus.—Calorimeter, balance and weights, ice, thermometer (0 to 50° in $\frac{1}{10}$°).

Make the necessary weighings of the calorimeter, stirrer, and water and determine the water equivalent of the calorimetric system, including the thermometer (see Exercise 19). Use about 200 g. of water at a temperature of 35–40°C. Carry out

the preliminary observations on this system as directed in the previous exercise. Wipe several small pieces of ice with a dry towel and drop them into the calorimeter after the last reading of the preliminary period. (Dryness of the ice is the most important factor in the success of this measurement.) Stir constantly until the ice is all melted and the required readings of the final period have been obtained. Reweigh the calorimeter and contents to determine the quantity of ice added. Make radiation corrections as in the previous exercise and make up a balance sheet as before. Define the term *heat of fusion of a substance.*

Exercise 21

THE EXPANSION OF A SOLID

(Pages 125–127)

Apparatus.—Expansion apparatus, metal rods, meter stick, thermometer (0 to 100° in 1°), two galvanized iron pails or other containers, stand, Bunsen burner, rubber tubing, clamp.

The problem is to determine the relation of the change in length of a metal bar to changes in its temperature. This study enables one to verify certain important statements made in the text and to acquire added familiarity with certain important concepts.

The expansion apparatus consists of a tubular jacket surrounding the bar to be measured. This jacket is to be filled with water at different temperatures and the changes in length measured. In the simplest type the changes in length are measured with a micrometer screw. To aid in telling when the screw makes contact with the end of the bar an electric circuit containing a bell or telegraph sounder is set up as shown in Fig. 26. A more accurate form of expansion apparatus uses two micrometer microscopes to measure the changes in length. Except for the details of measuring the changes in length, the manipulations are the same for both types.

Measure the length of the rod to be used (the length between index marks if the micrometer microscopes are used), set up the apparatus and familiarize yourself with the method of reading the measuring device by taking several practice readings at room temperature. Set one of the pails on the stand and connect it with the jacket by means of a siphon provided with a clamp for

controlling the flow. Fill the reservoir with ice water (or the coldest water readily obtainable), set the other pail in position to catch the out-flow, start the siphon and allow a stream of water to flow slowly through the jacket. When the temperature, as indicated by the thermometer, has become steady, set and read the micrometer. Repeat this setting twice at half-minute intervals, recording all three readings. They should agree within the limit of error of reading the micrometer. Heat the water in the reservoir by approximately 10° and repeat. Continue at 10° intervals and finally replace the reservoir by a steam generator and pass steam through the jacket. Prepare a sheet of coordinate paper and plot change of length as a function of tem-

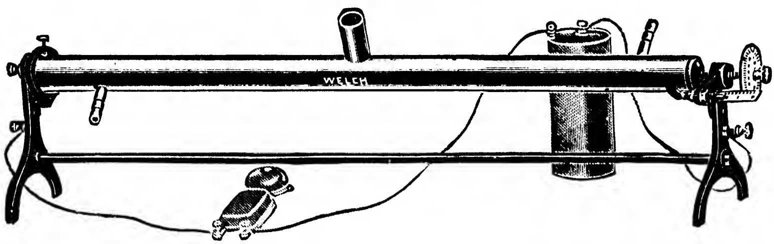


FIG. 26.—Apparatus for use in observing the change of length of a rod on heating. The temperature is controlled by allowing water from an elevated reservoir to flow slowly through the jacket.

perature. (This should be done for each point while waiting for the water to heat for the next reading.)

If time permits, substitute a rod of some other material and repeat, plotting both curves on the same sheet.

Discuss your results in the method presented in the text.

Compute the mean value of the coefficient of linear expansion for the material used and compare with the value given in the Handbook.

Exercise 22

THE MECHANICAL EQUIVALENT OF HEAT

(Pages 116–119)

This exercise affords a very complete review of much of the previous work since it involves the measurement of both mechanical and heat quantities with considerable accuracy.

The apparatus used is shown assembled in Fig. 27. Heat is produced by the friction between two brass cones contained in the

protecting cylinder beneath the large pulley. The outer cone is rotated by a belt passing around the lower pulley; while the inner cone is kept from rotating by the pull of the spring balance. The torque due to friction between the cones is equal to that due to the pull of the balance and the latter is easily computed.

You are to measure the work done in rotating the cone, and the heat developed. For the mechanical part you will need to know the value of the torque T required to keep the inner cone

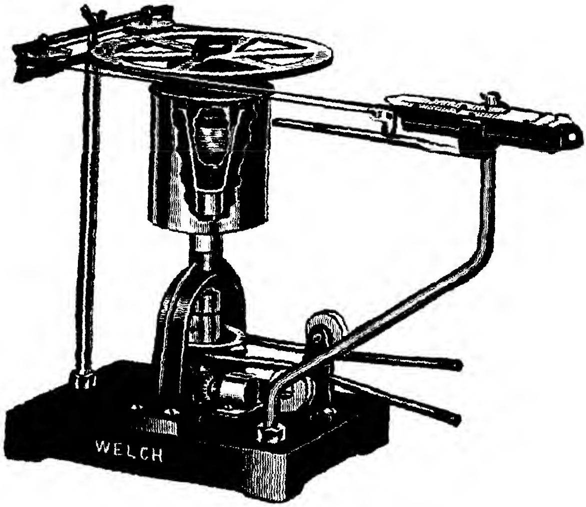


FIG. 27.—Apparatus for determination of the mechanical equivalent of heat. In some similar forms the torque due to friction is balanced by weights hanging over a pulley instead of as shown here. With such pieces a spring balance may be used by passing the cord under the pulley instead of over it. (The pulley will have to be raised to make the cord pull horizontally.) The spring balance has a considerable advantage in that equilibrium is automatically maintained.

stationary, and the number of revolutions made by the outer cone. The first of these quantities is simply the product of the balance reading F by the radius of the large pulley. The second is given directly by the difference in readings of the revolution counter attached to the apparatus. This must be multiplied by 2π to give the angle turned through in radians.

The heat measurements involve nothing new but must be made with care and corrected for radiation as previously described. The *mechanical equivalent of heat* is defined as the number of units of work which must be done to produce one unit of heat—in our case the number of gram centimeters which produce one calory.

Examine the apparatus carefully to make sure that you have a clear idea of its operation. Weigh the cones and stirrer to 1/10 g. Put *one drop* of sewing-machine oil in the outer cone and spread it well over the surface. Fill the inner cone about two-thirds full of cold water, reassemble the apparatus, and determine the force required to balance the frictional torque with the outer cone revolving at a speed as high as can be used without causing too much vibration. Remember that the less time required for the operation, the smaller the radiation corrections. The object of this preliminary work is to familiarize the student with the operation of the apparatus and to get all adjustments made so that the measurements may go off smoothly. It frequently happens that the torque exerted decreases rather rapidly after running for a short time. This is due to the fact that the viscosity (fluid friction) of the oil used to lubricate the cones decreases with rising temperature and the remedy is to use a lighter oil. With the heavier oils this effect is very pronounced. *No satisfactory results can be obtained unless the conditions remain sensibly constant during the run.*

Determine the volume of the thermometer bulb and compute the heat capacity of the calorimetric system. Add enough *cold* water to the inner cone to nearly fill it, making the total heat capacity of the system (cones, stirrer, thermometer, water) a whole number of calories per degeee in order to simplify the computations as much as possible.

Reassemble the apparatus and take the temperature readings required for the determination of the initial radiation rate. Read the revolution counter and start the motor immediately after the last reading. Keep the water well stirred at all times. During the heating interval, read temperatures as closely as possible at half-minute intervals and continue until the final temperature is about as far above room temperature as the initial was below. Also record the balance reading at each half-minute interval during the run. Shut off the motor at the end of some half-minute interval and continue reading the thermometer until the final radiation rate is well established. Compute the radiation correction as previously directed (Exercise 19). Since the thermometer used is graduated in tenths of degrees and half this can be estimated, the temperatures at the beginning and the end of the operation should be correct to about 0.05°. Read the revolution counter again and compute the work done, the quantity of

heat developed, and the mechanical equivalent of heat at once. If time permits, make a second set of measurements. Tabulate your data neatly and have it checked by the instructor before leaving.

GROUP V

THE GAS LAWS

Exercise 23

BOYLE'S LAW

(Pages 152–154, 159)

Apparatus.—The apparatus used is similar to that shown in Fig. 28.

A body of dry air is confined in a closed graduated tube which is connected by a rubber tube to an open tube, the lower part being filled with mercury. If the barometric height is B, and Δh the difference in mercury levels in the two tubes, the pressure P on this inclosed air is evidently

$$P = B \pm \Delta h.$$

Make a series of at least fifteen observations beginning with the lowest pressure available, and continuing by approximately equal steps to the highest. Read the barometer and estimate Δh to tenths of millimeters. Tabulate results to show V, Δh, P, and the product PV. Also plot the P-V curve using pressures as ordinates. This curve is often called the "isothermal (equal temperature) for the perfect gas." What kind of a curve is it?

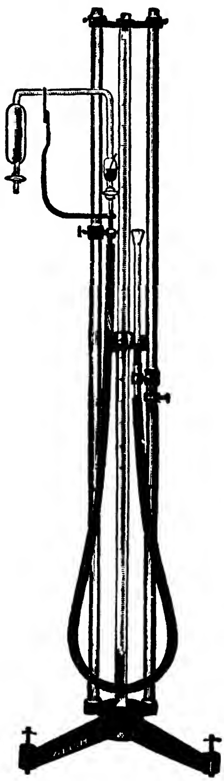


FIG. 28.—Boyle's Law apparatus.

Exercise 24

THE VOLUME-TEMPERATURE RELATION FOR A PERFECT GAS

CHARLES' LAW AT CONSTANT PRESSURE

(Pages 154–156)

Apparatus.—Constant-pressure air thermometer, thermometer (0° to 100° in degrees), ice, Bunsen burner, support, beaker. The apparatus is shown in Fig. 29.

A body of dry air contained in the bulb T_1 of known volume is surrounded by a variable temperature bath B and connected by a capillary tube to the graduated tube T_2. The pressure is kept constant by raising or lowering the mercury reservoir R. When the bath B is heated a part of the air in T_1 passes into T_2 where it remains at room temperature. *Thus the observations are made with a varying mass of air.* Corrections for this must be made as explained later.

With the whole apparatus at room temperature and T_1 open to the outer air, raise the reservoir R until about 15 c.c. of air remain in T_2. Close the stopcock and record the room tempera-

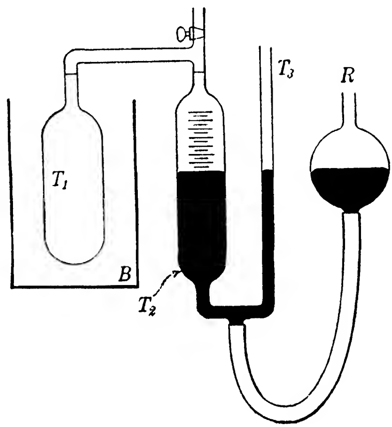


Fig. 29.

ture and the volume of air in T_2. You will readily perceive that the settings and readings which determine the volume of air in T_2 are somewhat troublesome as well as very important. All readings must be made with care and all settings checked.

Fill the bath B to the index on the capillary with finely cracked ice and water, keep the bath well stirred for several minutes, and adjust R until the mercury stands at the same level in T_2 and T_3. Again record the volume of air in T_2. Replace the ice with water about 15° above room temperature and again record the volume of air in T_2. Continue by 15° steps until the bath is boiling.

Allow the bath to cool (this may be hastened by adding cold water or ice) and secure a similar set of readings with falling temperatures. This set may end at room temperature.

Correction for the Quantity of Air Removed from T_1.—The volume (at room temperature) of the air which has been forced out of T_1 at any time is equal to the change in the volume of air in T_2 starting from room temperature. Thus, at any given temperature, T_1 is filled by a mass of air which, when at room temperature, occupied a volume less than that of T_1 by an amount equal to the increase in volume (ΔV) of air in T_2. It follows that, had the whole mass of air which was originally contained in T_1 taken part in the expansion at all stages, the changes in volume ($\Delta' V$) corresponding to a given change in temperature would have been greater than those actually observed in the same ratio that the whole volume (V_0) of T_1 bears to the initial (room temperature) volume of the air which fills the bulb at any stage. Thus if it had been possible to keep the mass of the gas constant, the expansions ($\Delta' V$) would have been those computed from the equation

$$\Delta' V = \left(\frac{V_0}{V_0 - \Delta V}\right) \cdot \Delta V$$

and the volumes (V_t) corresponding to the several temperatures by the relation

$$V_t = V_0 + \Delta' V$$

where V_0 is the volume of the tube T_1. Plot a curve using values of V_t and the temperatures as coordinates and discuss fully. From the slope of this curve compute the mean coefficient of expansion of air. Tabulate results as shown.

Temperatures rising				Temperatures dropping			
Temperature	T_2	ΔV	$\Delta' V$	Temperature	T_2	ΔV	$\Delta' V$

Mean apparent coefficient of expansion. . . . .
Divergence from accepted value (0.003673). . . . . .percentage of error. . . . . .

Exercise 25

THE PRESSURE-TEMPERATURE RELATION FOR A PERFECT GAS

CHARLES' LAW AT CONSTANT VOLUME

(Page 156)

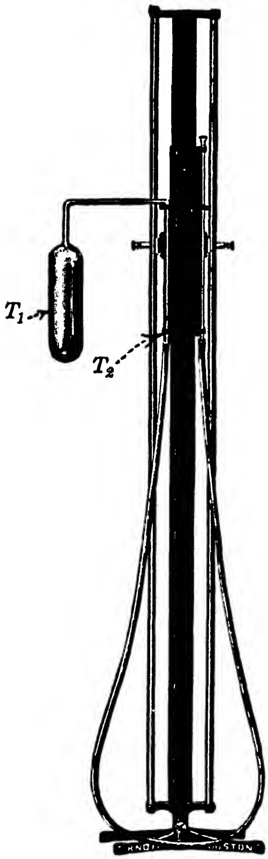


FIG. 30.—The constant volume air thermometer. In use the bulb is surrounded with a vessel containing water which may be kept at any desired temperature.

Apparatus.—Constant-volume air thermometer (Fig. 30), bath, ice, Bunsen burner, stand, heater, thermometer (0° to 100° in degrees), barometer.

Caution. *To avoid getting mercury into the bulb always leave the mercury level well down in T_2 except when actually making a setting.*

Surround the bulb with finely cracked ice and water and allow to stand for from 3 to 5 min. Bring the mercury level in the capillary to the index, read the mercury levels in both tubes, and, also, take the barometric reading. The pressure on the inclosed air is then $B + \Delta h$ where B is the barometric height and Δh the difference in mercury levels. *Be sure that temperatures are constant before taking readings.* Replace the ice by water at room temperature and repeat. Continue by 15° steps until the bath is surrounded by boiling water. Keep the bath well stirred at all times and read temperatures to $\frac{1}{10}$°. Allow the bath to cool slowly and take a second set of readings with falling temperatures.

While taking these readings plot a curve showing the pressure-temperature relations. Project it back to cut the temperature axis and discuss fully. Compute the mean value of the temperature coefficient of pressure increase at constant volume $\frac{p_t - p_0}{p_0 \cdot \Delta t}$ from your observations and compare with the accepted value. Discuss your results fully and in particular develop the concept of the *absolute zero* and the absolute scale of temperature.

Exercise 26

THE VAPOR PRESSURE OF A SATURATED VAPOR

Apparatus.—Six vapor pressure tubes (Fig. 31), 3 tall beakers, meter sticks, thermometers, bunsen burner, and supports.

Examine the tubes. Notice that each set consists of six tubes, three of which are open to the air, while three have been exhausted and sealed. Tags attached to the tubes indicate the liquid in each. The tubes of one pair contain ethyl alcohol, those of a second pair ether, and those of the third a mixture of the two. You are expected to obtain data sufficient to enable you to plot the *P-T* curves for the three liquid-vapor systems over a range extending from 0°C. to a temperature such that the vapor pressure is about 2 atmospheres.

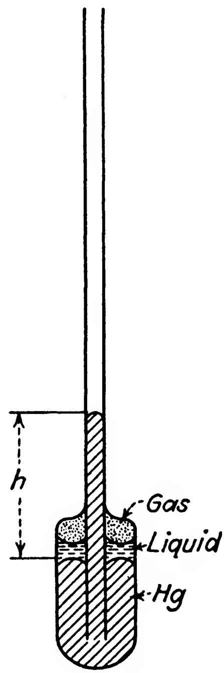


FIG. 31.

There are many observations to be made and it will be necessary in each case to make sure that equilibrium has been reached. It is, therefore, important to arrange matters so that the work may go on as rapidly as possible and that as little time as possible be wasted waiting for something to happen. Before you begin, prepare a graph sheet allowing a pressure range of from 0 to 150 cms. mercury and a temperature range of from 0 to 100°C. Plot the result of each observation *as taken* so that the curve will be complete when the last observation has been made.

Set up the three closed tubes, immersing the bulb of each completely in a bath at 0°C. (Use plenty of finely shaved ice.) After about two minutes make the necessary observations and compute the vapor pressure of each liquid. Repeat after about 1 min. to make sure that equilibrium has been reached.

Replace the ice water by tap water and repeat. Also record the temperature of the tap water. Continue at about 10° steps until the vapor pressures are slightly above 1 atmosphere. This

condition is, of course, reached at different temperatures for the different liquids.

Change to the open tubes and continue up to pressures of about 2 atmospheres.

Your report should be a short essay on the subject of saturated vapors illustrated by use of your data.

Exercise 27

HUMIDITY

(Pages 182–189)

To measure the absolute humidity of the air directly it would be necessary to remove all the water vapor from a known volume of air and weigh it. To do this one might take advantage of the fact that water vapor is readily and completely absorbed by such drying agents as calcium chloride and phosphorus pentoxide. One might, then, arrange a series of drying tubes connected to a large bottle full of water and by siphoning a known weight of water from the bottle draw an equal volume of air through the drying tubes. The increase in weight of the tubes would thus be equal to the weight of water vapor originally contained in the known volume of air.

Since this direct method is somewhat tedious and also because the *relative humidity* is of more importance in meteorology, determinations of humidity are always made by indirect methods. Of these the wet-and-dry-bulb method and the dew-point method are the most important. The wet-and-dry-bulb hygrometers used by the Weather Bureau consist of two thermometers mounted as shown in Fig. 32. The dry bulb registers air temperatures, but the wet bulb is cooled by evaporation from the cotton wick which is moistened with water at air temperature. In use the hydrometer is kept in moderately rapid rotation and readings are taken about every minute until the temperature of the wet bulb becomes constant. The relative humidity (and if desired also the absolute humidity) is then found from the hygrometric tables, a copy of which is supplied with the apparatus.

The dew-point apparatus (Fig. 32*a*) contains a volatile liquid which is caused to evaporate by blowing air through it. When this liquid has been cooled to the temperature at which the

surrounding air becomes saturated (the dew point), a film of moisture dulls the brightly polished metal surface. If evaporation stops, the apparatus warms up and this film disappears. The temperature of appearance and disappearance should be noted and their mean taken as the dew point. Again the relative humidity can be obtained from the hygrometric tables if the air temperatures and dew point are known. Use both types of apparatus to determine the humidity in the laboratory and out of doors. Do your results agree reasonably well? What are some reasons why a knowledge of the relative humidity is important? How could hygrometric tables like those used be prepared? Which is heavier, dry air or moist air? Write a short essay on "The Water Vapor in the Air" as your report.

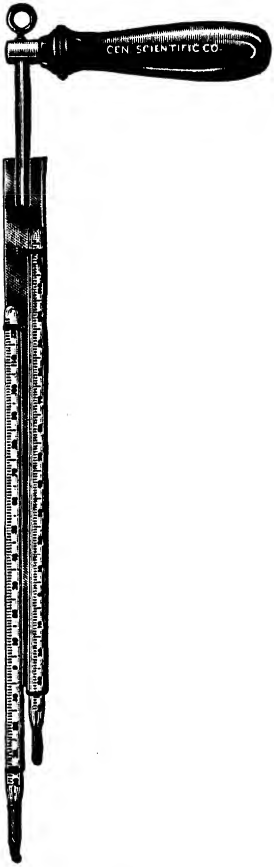


FIG. 32.—Wet-and-dry-bulb hygrometer.

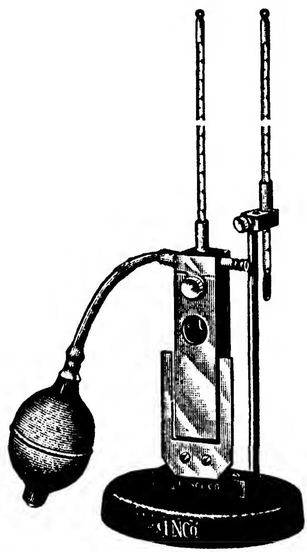


FIG. 32*a*.—Dew-point apparatus.

GROUP VI

SIMPLE HARMONIC MOTION

Exercise 28

THE PERIOD OF VIBRATION OF A LOADED SPRING

(Pages 250–254 and Exercise 3)

Apparatus.—Joly balance (as used in Exercise 3), weights, stop watch, stand with pointer to serve as index.

It is shown that the period of vibration of a loaded spring is given by the relation

$$T = 2\pi\sqrt{\frac{m}{c}},$$

where m is the load carried by the spring, including a portion of the weight of the spring itself, and c is the force in dynes required to stretch the spring 1 cm.

Determine the value of the force constant c for the spring as was done in Exercise 3.

Unhook the spring from the index and swing the glass tube together with the index and pan to one side so that it will not interfere with the vibrations of the spring. Remove the spring and weigh it to $\frac{1}{10}$ g. Replace, set the index on one side to mark the position of the lower end of the spring when at rest, and determine the period of vibration of the spring alone. To do this stretch it by a moderate amount (5 to 10 cm.); start the stop watch just as the lower end of the spring passes through its position of rest in the upward direction, and count 1 on the next upward passage. Take the time for a considerable number of vibrations and compute the period. Check by a second determination.

Hang a small weight on the spring and determine the period of the loaded spring. Repeat for about a half dozen loads up to the maximum load which the spring can carry without stretching it

beyond the limits of the apparatus. Check each determination carefully.

Plot a curve with values of T^2 as ordinates and loads as abscissæ, and prolong it to cut the x-axis. What is the *effective mass* of the spring itself? What fraction of the actual mass? Why is this less than the actual mass of the spring? (By *effective mass* is meant the mass which would have the same effect if attached to the bottom of the spring as the whole spring actually has.)

In connection with your report derive the equation used, starting from the fundamental equation (defining equation) of simple harmonic motion.

Exercise 29

SIMPLE PENDULUM

Precise Determination of the Acceleration Due to Gravity

(Page 254)

Apparatus.—Simple pendulum with mercury contact, master clock also with mercury contact, telegraph sounder, meter stick, vernier calipers.

The direct determination of the acceleration of a freely falling body can be made without difficulty (Exercise 11) but the results are never of very great accuracy because of the effects of friction and the need of measuring either large velocities or small time intervals with great accuracy. It is easy to show that the period of a simple pendulum is given by the equation

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where l is the length of a simple pendulum, T its period of vibration and g the acceleration due to gravity. The problem of determining the acceleration is thus reduced to the comparatively simple one of measuring a length and a time interval.

The simple pendulum used in this experiment consists of a heavy ball suspended by a fine steel wire. This is arranged (Fig. 33) so that it and the clock pendulum or master pendulum form parts of an electrical circuit containing a telegraph sounder.

This circuit is closed only if *both* pendulums are near the midpoints of their paths at the same instant. It is convenient to regard the two pendulums as switches or keys controlling the electric circuit. Obviously the sounder can operate only if both keys are closed at the same instant.

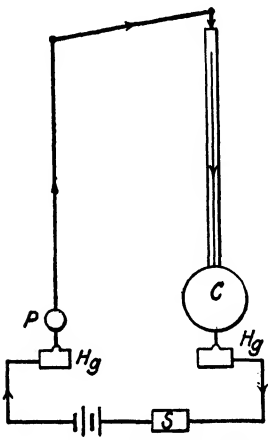


FIG. 33.—Diagram of electrical connections for method of coincidences.

Measure the Length of the Pendulum. This must be done with the greatest possible accuracy. Use a meter stick with adjustable jaws attached to measure the distance from the point of support to the top of the ball, and vernier calipers to measure the diameter of the ball. Add half the diameter of the ball to the length of the wire. Make at least three independent determinations of the length of the pendulum and use the average to tenths of millimeters.

Determination of Period. Method of Coincidences.—Complete the electrical circuit, adjust the level of the mercury in the pendulum contacts so that with the simple pendulum at rest the sounder clicks each time the clock pendulum passes through its central position. Draw the simple pendulum aside a small distance and release it. It should swing through an arc of not more than one-tenth radian without any twisting of the wire. Much of the success of the experiment will depend upon the smoothness of swing of the pendulum. Note the hour, minute, and second at which the sounder clicks. This gives a time at which the two pendulums were both near their central positions (within the width of the mercury contact certainly). In the same way note the time of the next click of the sounder. The interval between these clicks is equal to the time required for one pendulum to gain a half vibration on the other. Continue to note and record coincidences for 3 or 4 min. in order to establish the length of this interval with some exactness, and after that allow the pendulum to continue undisturbed for later observations. Record as shown below. After this period is determined allow the pendulums to continue swinging for several minutes and again determine the time of coincidence. (Observation marked *n*th in example.)

In the set of observations given as an illustration the first five readings showed that the coincidence period was between 44 and 45 sec. As will appear, it is of no particular importance which value is taken since either will do for our needs. The variation arises from the fact that the mercury contacts are of considerable width so that the two pendulums do not have to be exactly at the midpoints of their paths to close the circuit. It will be seen that in this case observations were continued for nearly a half hour but that it was necessary to count only five vibrations.

TABLE I.—DATA FOR METHOD OF COINCIDENCES

	Times of coincidence Hr.	Min.	Sec.	Intervals in seconds
First	5	16	58	
Second	5	17	42	44
Third	5	18	27	45
Fourth	5	19	12	45
Fifth	5	20	56	44
nth	5	24	22	
n'th	5	28	49	
n''th	5	32	30	
n^*th	5	42	07	

The period may now be computed as follows: Elapsed time from 5–16–58 to 5–24–22 is 7 min. 24 sec. or 444 sec., coincidence interval 44 sec. therefore:

Number (n) of coincidences = 444/44 = 10 (nearest whole number).[1]

If the pendulum has a shorter period than the clock it must have made exactly 10 more half vibrations than the clock pendulum in the 444 sec., that is, 454 single (half) vibrations. If the clock pendulum beats seconds, the half period of the simple pendulum is, then, 444/454 sec.

Allow the pendulum to continue swinging and make two or three other determinations as in the example, computing the period in each case. Repeat the whole timing process. Remember that the longer the pendulum swings the more accurate the

[1] NOTE.—The same result would be obtained if 45 sec. was used as the coincidence interval.

result. Your two independent determinations ought to agree to about 0.0001 sec.

Use these results to compute the acceleration due to gravity and compare with the tabular values for your latitude and elevation. What is the greatest source of error?

It will frequently happen that the sounder clicks more than once at each coincidence period. If two clicks are heard you may take the time of either (but always the same one) the first or second. If three, the time of the second. There ought not to be more than three unless the periods are very nearly the same and the amplitude has become very small. In this case it is best to change the conditions of working.

Exercise 30

ROTATIONAL HARMONIC MOTION. MOMENT OF INERTIA

(Pages 101–105, also 253–255)

Apparatus.—Simple harmonic motion of rotation apparatus, weights, vernier calipers, stop watch.

The work of this exercise parallels step by step that of Exercise 28. The sole difference is that here we are dealing with motion of rotation, there with translation. This is a special case of a very general and important analogy. *Every translational quantity and every translational relation has its rotational analogy and the equations of rotational motion may be obtained from those of translational motion by replacing the symbols which represent translational quantities by those representing the corresponding rotational quantities.* Thus a uniform motion of rotation is analogous to a uniform motion of translation, a uniformly accelerated rotational motion to a uniformly accelerated motion of translation, rotational simple harmonic motion (s.h.m.) to translational s.h.m., etc.

Pursuing this analogy we define s.h.m. of rotation by an equation $\alpha = -c'\Theta$ (Greek letters are used for rotational quantities) which is the analog of $a = -cx$. (The defining equation of s.h.m.) This defines rotational s.h.m. as *that type of rotational motion in which the angular acceleration* α *(in radians per second*^{2}*) is directly proportional to the angular displacement* Θ *(in radians)* and in the opposite directions. You may also remember that, in the c.g.s. system $F = ma = -cmx$ where F is the force (in dynes) tending to undo the displacement. By analogy, the

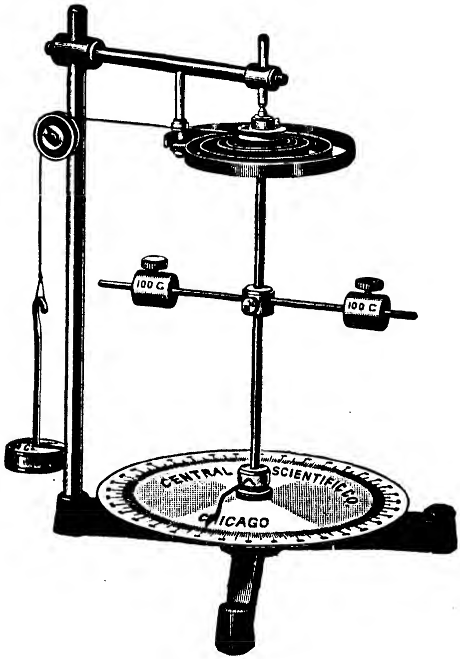
corresponding rotational equation must be $T = I\alpha = -c'I\Theta$ where T is the restoring torque in dynes at 1 cm. radius due to a displacement of Θ radians and I is the *rotational analog of mass.* The fundamental equation of dynamics $F = ma$ may be written as the defining equation of *mass* in the form $m = F/a$ and in like manner we may define the rotational quantity represented by the symbol I above by the equation $I = T/\alpha$. This quantity is called the "*moment of inertia*" of the rotating system and is (at least for the beginner) best defined as *the quantity which plays the same part in all equations of rotational motion that mass (inertia) does in the equations of translatory motion.* It is the chief purpose of this exercise to serve as an introduction to this important concept.

Examine the apparatus carefully and see that it seems reasonably free from friction, etc. Note the type of motion which ensues when the bar is turned away from its position of rest and released. In what respects does it appear to resemble s.h.m.?

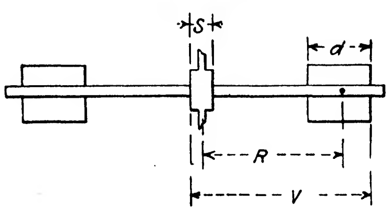
Place the weight carrier in position and note the reading of the index to $\frac{1}{10}$ division. Repeat several times and average. Add weights enough to cause a deflection of about 10 deg. and again record the average reading. Repeat for five loads. Measure the radius of the pulley to which the weights are attached and compute the restoring torque (dynes at 1 cm. radius) and the ratio of torque to displacement (in scale divisions) in each case. If any readings appear to be far out of line check carefully before going on. Do these results justify the conclusion that this is s.h.m. of rotation as defined above? Is there any limitation on the amplitude of the vibration? From the observations compute the torque constant (c) of the spring; *i.e.*, the torque in dynes at 1 cm. radius required to cause a deflection of 1 radian (scale divisions are degrees). If this is not constant for all deflections use the value for *small* deflections.

Remove the sliding masses from the cross-arm and the weight carrier from the string; set the apparatus in vibration and determine the period with a stop watch. Count as many vibrations as possible and make and record at least three trials. Replace the sliding masses, placing them as close to the axis as possible and clamping tightly. Measure the distance between the centers of gravity of these sliding bodies with a vernier caliper, also the dimensions of each. Determine the period of vibration with the masses in this position and repeat for four other positions.

Be sure that in each case the distance R from the axis to the center of gravity is the same for each body; *i.e.*, that they are symmetrically placed with respect to the axis. This is most con-



(*a*)



(*b*)

FIG. 34.—Apparatus for s.h.m. of rotation and diagram showing how the masses may be placed for convenient computation.

veniently done as follows: Measure the diameter (s) of the support (Fig. 34b) and the length (d) of the sliding body. The distance R from the axis to the center of gravity of the sliding body is $V - \left(\frac{s + d}{2}\right)$. It will simplify computations if whole number

values of R are used, which may be done by setting the vernier to read $R + \left(\frac{s + d}{2}\right)$ and taking R as a whole number. For example, in one case it was found that s was 2.22 cm., d, 1.48 cm. $\frac{s + d}{2} = \frac{2.22 + 1.48}{2} = 1.85$. In order to have $R = 3, 4$, etc. cm., the vernier is then set at 4.85, 5.85, etc., placed in position and the sliding body moved out to the outer jaw. The other ball is then placed in the same way.

Make a second set of observations using the heavier bodies placed at the same points. How does the moment of inertia depend upon the mass of these bodies?

Since this motion is analogous to that of the vibrating spring, we may write our equation by substituting rotational quantities in the equations of Exercise 28 as follows:

$$F = ma = -cx, \qquad T = I\alpha = -c'\Theta,$$

$$T = 2\pi\sqrt{\frac{-x}{a}} = 2\pi\sqrt{\frac{m}{c}}. \qquad T = 2\pi\sqrt{\frac{-\Theta}{\alpha}} = 2\pi\sqrt{\frac{I}{c'}},$$

whence

$$I = \frac{c'T^2}{4\pi^2}.$$

From the values of torque constant and period obtained above, compute the moment of inertia for the support alone and for each position of the sliding weights. Notice that $\left(\frac{c'}{4\pi^2}\right)$ is a constant. Hence the computations are shortened if one simply looks up values of T^2 in the tables (Handbook) and multiplies by this constant. Plot a curve showing the relation between I and R^2. What does the curve show as to the way in which the moment of inertia of the system depends upon R?

GROUP VII

SOUND

Exercise 31

RESONANCE OF AIR COLUMNS

(Pages 268, 278)

Apparatus.—Resonance tube with water reservoir, several tuning forks, meter stick, rubber hammer.

Mount the fork with the lower edge of its prongs about ½ in. above the tube. Have the water in the tube about 10 cm. from the top. Set the fork in vibration by striking it with the rubber hammer at a point about one-third the way back from the end, and cause the water to run rapidly out of the glass tube by lowering the reservoir. Note approximate position of any resonance points. (There should be at least two.) If necessary, repeat, being careful to keep the fork vibrating strongly. Finally locate these points as precisely as possible. (Rubber bands on the tube make convenient markers.)

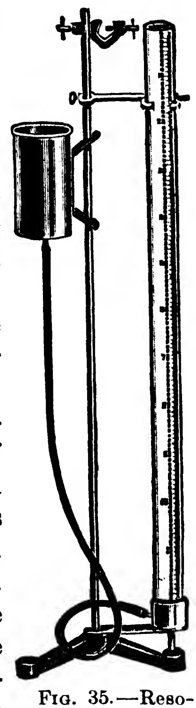


FIG. 35.—Resonance take with reservoir.

The final determination is best made by running the water back and forth for a distance of a few centimeters on each side of the band and moving the latter until the maximum loudness comes just as the water is at the marked level. In this way locate two resonance points. Measure the distance between them and also the distance from the upper end of the tube to the first resonance point. The distance between resonance points is exactly one-half wave length; that to the first slightly less than one-fourth wave length, since the waves are reflected from the air slightly *above* the opening. What correction would you need to add to the distance to the first node to take account of this? How does this compare with the radius of the tube?

Using the half wave length as determined and the known frequency of the fork, compute the velocity of sound from the relation

$$\text{Velocity} = \text{frequency} \times \text{wave length}$$

and compare with that obtained from the relation

$$V_t = V_0 \sqrt{1 + 0.00367t},$$

where V_0 is the velocity of sound at 0° and t the room temperature. (Look up the value of V_0 in the Handbook.)

Repeat, using a fork of different frequency. Don't forget that the real object of this exercise is the study of *resonance*,—not the measurement of the velocity of sound.

Exercise 32

THE MODES OF VIBRATION OF AN AIR COLUMN

(Chapter XXIX)

Apparatus.—Siren disk, variable speed rotator, revolution counter, small motor, source of compressed air (a foot bellows will do), several glass tubes from 4 to 8 cm. in diameter, stop watch, thermometer. (A hand rotator with revolution counter may be used if the variable speed piece is not available).

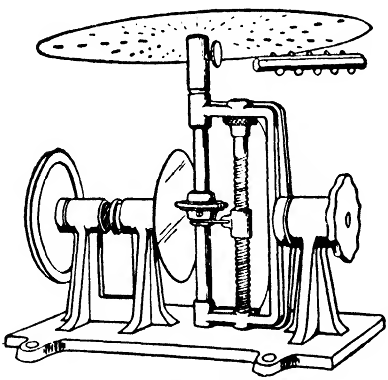


FIG. 36.—Variable speed rotator and siren disk.

Set up the apparatus with one of the tubes supported in a vertical position directly above the outer row of holes in the disk. Blow a steady stream of air against this row of openings from below and start the disk, increasing the speed slowly until the first resonance is obtained. Adjust the speed for maximum resonance (loudness) and determine the number of r.p.m. of the disk. Compute the frequency of the impulses imparted by the puffs of air entering the tube. Continue to increase the speed and determine resonance points up to the highest speed

which can be used. Tabulate the resonance frequencies and show that they are approximately in the rations 1:2:3, etc.

Close the upper end of the tube by means of a cardboard box cover which fits tightly over the end and repeat. Compare the frequencies obtained with the "closed pipe" with those in the previous case.

Determine the frequency of the fundamental (lowest) tone for each of several tubes. Measure the length and inside diameter of each tube. Assuming that the wave length is exactly twice the length of the tube compute the velocity from your observations for each tube. Is there any systematic difference in these values? How does their mean compare with that computed from the relation

$$V_t = V_0\sqrt{1 + 0.00367t},$$

where V_0 is the velocity at 0° (Handbook) and t the temperature of the room. How does your result agree with that computed? Could you explain this difference by supposing that the reflections actually take place in the layers of air just outside the tube so that the wave length is actually $(2l + ar)$ where r is the radius of the tube and a some constant? If your results are sufficiently accurate to show a systematic *decrease* in the experimental results with the size of the tube it will be of interest to compute the values of a by substituting the correct value of V_t in the equation

$$V_t = n(2l + ar).$$

(Solve the equation for a before substituting values.)

Read the barometer. Compute the density of air in the room and the theoretical velocity of sound, using for the latter the

$$V = \sqrt{\frac{1.41P}{d}}$$

relation where P is the pressure of the air in dynes/cm.^{2} and d the density in grams per cubic centimeter.

What harmonics are possible in an open organ pipe? In a closed pipe? What is the cause of the differences in "quality" shown between the different "stops" of a pipe organ? What effect would a sudden change in temperature be likely to have on a pipe organ?

Exercise 33

THE VIBRATION OF STRINGS

(Pages 248, 277)

Apparatus.—Sonometer, weights, tuning forks, rubber hammer.

Hang weights enough on the wire to stretch it tightly, so that when plucked it gives a clear musical sound of rather low pitch. Place one of the bridges near the left-hand end and vary the length of the vibrating segment by sliding the other back and forth. What effect does the length of the segment have on its pitch?

Set a tuning fork having a pitch of middle C (256 vibrations per second) in vibration and try to find a length of string which

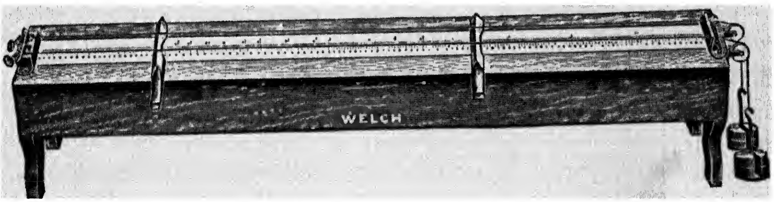


Fig. 37.—Sonometer.

will have the same pitch. This will be easy if you have a good "ear" but less fortunate individuals will find it better to use a method depending upon the fact that when the string has the same frequency as the fork it will be set in vibration if the handle of the vibrating fork is held firmly against the resonance box. This is an example of resonance or "sympathetic vibrations." A light rider made by folding a strip of paper about 2 cm. long and 2 mm. wide serves as a convenient indicator for these rather weak sympathetic vibrations. If such a rider is placed on the wire, the vibrating fork held against the box, and the bridge moved steadily in one direction, the rider will remain at rest until the proper length is nearly reached and be strongly agitated or even thrown completely off when the adjustment is perfected.

When the fork and string have been brought nearly into unison listen for beats and try to *feel* them by resting the finger tips lightly on the box. These alternations of loudness are caused by the interference of the two wave systems and since the number of beats per second is equal to the difference in vibration frequency perfect unison may be reached by moving the bridge

in such a way that the beats become slower and slower and finally die out altogether.

When a satisfactory setting has been reached measure the length of the segment between the bridges. What fraction of a wave length is this? What is the velocity of a transverse wave along the wire under these conditions?

Repeat for the forks giving the major chord (C-E-G-C′) and note the relative lengths of the segment in each case.

Add weights enough so that the tension is four times as great and repeat these observations. How do the lengths in this case compare with those in the other? Use the heavier wire with the same tension for at least one determination. What factors determine the pitch of a string? How are these facts utilized in the construction of a piano? How is the tuning of a piano done? What effect upon the pitch of a piano would you expect a fall of 10°C. in temperature to have?

Exercise 34

INTERFERENCE OF WAVES—STANDING WAVES IN AIR

(Page 248 and Chapter XXVII)

Apparatus.—Kundt's tube, cork dust, resin, cloth, clamp, thermometer.

Distribute the cork dust evenly along the tube and clamp the latter firmly to the table. Clamp the brass rod at its midpoint being sure that the plunger on the end is free from the tube; rub a liberal amount of powdered resin into the cloth and stroke the free end of the rod briskly with this resined cloth. Do not grip the rod too hard while doing this. Pinch it *lightly* between thumb and finger and pull *straight* back. Students often have considerable difficulty in getting the rod to vibrate strongly and this is usually due either to gripping it too tightly and working too hard or to pulling laterally on the rod so that the plunger on the end strikes the side of the tube. Also it sometimes happens that the rod gets gummed up by resin which has stuck to it. When you have caught the trick of getting a clear high note your companion should adjust the length of the air column between the two rods until the cork dust is thrown up violently at some points and hardly at all at others. Measure the distance between nodes, count the segments of the air columns, and compute the wave

length of the air waves. Try to picture clearly conditions in the tube while sounding.

Note the room temperature and compute the velocity of sound in air at that temperature as in the previous exercises. Knowing the velocity of the sound and its wave length in air compute the frequency of the note. How is the length of sound wave in the brass rod related to the length of the rod itself? (Remember that

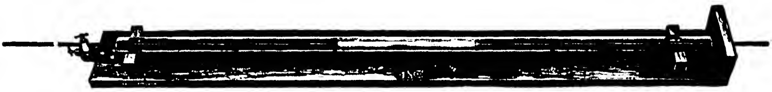


Fig. 38.—Kundt's apparatus.

the conditions are such that there is a node at the middle and an antinode at each end.)

What is the velocity of sound in the material of which the rod is made? Check by reference to Handbook.

How could such a tube be used to find the velocity of sound in carbon dioxide? If you are interested in a piece of more independent work you might try to outline a procedure by means of which you could measure the ratio of the two specific heats of carbon dioxide by means of this apparatus (see pp. 162 and 270, text).

GROUP VIII

ELECTRIC AND MAGNETIC FIELDS

Exercise 35

ELECTROSTATICS

(Chapter XXX)

It has been shown in the lecture room that an electrified or charged body is distinguished by its property of attracting such light bodies as particles of dry sawdust, bits of paper, hair, etc. It has also been shown that the electroscope offers a more sensitive means of detecting and classifying electrified bodies. It is the purpose of this series of experiments to afford you an opportunity for first-hand experience with such bodies. Since both the phenomena and our method of explaining them are very simple, these experiments afford a very perfect illustration of the methods of inductive reasoning. It is well to remember that it is far easier to *follow* such an inductive process than to *discover* it. You may cover in the work of an afternoon a field which required a period of 300 years in its exploration. Most such inductive processes begin with a question (either explicit or implied), proceed through experimental additions to our knowledge and end in a generalization which constitutes an answer to the original question.

Apparatus.—Rods of various materials; flannel, silk, cotton, rayon cloths; box of sawdust; electroscope; two insulated spheres; silk and cotton thread; wire; glass tube; caps of silk and flannel to fit charging rods and with silk threads or cords for handling; electrophorus; small glass tube 3 ft. long; thread of various sorts.

A. What Bodies Can Be Electrified by Friction (Contact) with Other Bodies?—You are supplied with a considerable number of materials including rods of brass, iron, hard rubber, glass, sulphur, cakes of waxes, and cloths of various sorts. Classify these materials, as Gilbert did, into "electrics" and "non-electrics."

B. What is the Difference between "Electrics" and "Non-electrics?"—You are supplied with a brass sphere supported on a glass or rubber rod, an electroscope, a glass rod or tube, threads and wire. Connect the brass cylinder to the electro-

FIG. 39.—Apparatus for Experiments in electrostatics; *a*, electroscope; *b*, electrophorus; *c*, wire cylinder; *d*, insulated spheres; *e*, hollow sphere; *f*, egg shaped conductor; *g*, proof plane; *h*, rod and cloth; *i*, rod with silk cap.

scope, using each of these materials in turn. In each case, note the effect of touching the cylinder with a charged rod. Also, try a moistened thread and a glass tube which has been wiped off with a damp cloth. Classify the materials used with respect to their ability to conduct electricity. On the basis of these

observations, explain the difference between electrics and non-electrics. Confirm your reasoning by trying to electrify a brass rod held in a bit of dry rubber tubing. Why is it difficult to electrify a glass rod in damp weather? Try wiping your glass rod with alcohol. Does it work better? Why?

C. What Determines the Sign of the Charge on a Rubbed Body?—Charge the electroscope by touching it with either a glass rod rubbed with silk (positive), or a rubber rod rubbed with fur or flannel (negative). Bring each of the two charged rods, in turn, near the electroscope and note the results. Also note the effect of bringing an uncharged body near the electroscope.[1] How may the electroscope be used to determine the sign of the charge on any body?

Using the same materials as in Part 1, try to find some material which becomes positively charged when rubbed with any of the others. Two rods may be rubbed together by stroking one with the other. Continue tests until you can arrange a table such that any material will be positively charged if rubbed with one which occupies a later place in the list.

Try electrifying a glass rod by rubbing it on the palm of the hand. Is the result ever any different when the rod is rubbed on the forearm?

State the "two-fluid" theory of electricity and show how its assumptions might be used to explain these results. Do the same for Franklin's "one-fluid" theory and also for the modern electron theory. Compare the latter with the one-fluid theory. Does there appear to be any reason to suppose that the modern theory rests upon a sounder basis than the older ones?

D. Are Both Bodies Charged during the Operation of Rubbing Them Together?—Stroke a rubber rod with a glass rod and test both. Test several other combinations in the same way.

E. What are the Relative Magnitudes of the Two Charges Produced by Rubbing One Body with Another?—You are provided with silk and flannel caps which fit over the charging rods used in the previous experiments, a brass plate which replaces the knob of the electroscope, and a metal can which can be placed on this plate. Slip the flannel cap on the rubber rod (be sure that neither is charged to begin with), twist the cap

[1] To make sure that a body is completely uncharged pass it quickly through the flame of a Bunsen burner or hold it above the flame for a minute or two.

around two or three times and then put the covered end of the rod inside the can, which has been placed on the uncharged electroscope. Next, pull off the cap (handle it by the silk cord) and test both it and the rod separately. What do these results show? Can you explain the divergence of the electroscope leaves in terms of the electron theory?

F. Charging a Body by "Induction."—Arrange two insulated brass cylinders or spheres so that they touch one another, bring a charged rod near one of them and separate them while the rod is in position. Test each cylinder and interpret your results in terms of the electron theory.

Discharge the electroscope and perform the following operations noting carefully the effect of each:

a. Bring a charged body near the plate or knob of the electroscope.

b. Touch the knob with your finger.

c. Remove your finger.

d. Remove the charging body.

e. Test the sign of the charge on the electroscope.

Explain all observations carefully in terms of the electron theory.

G. The Electrophorus.—This a simple device with which one can obtain a large quantity of electricity (theoretically, an unlimited quantity) by induction from a single charge. It consists of a "bed" of some insulating material and a metal "cover" having an insulating handle.

Electrify the bed by rubbing it with some suitable material. Test the sign of the charge. Put the cover on the bed, remove it and test. Repeat several times to be sure of the result. Is any electricity removed from the bed by this process? Why? Next touch the cover while it is in place on the bed and again remove and test with the electroscope. Note any other evidences of electrification. Explain carefully using a series of diagrams to illustrate the location of the charges (both positive and negative) during the various stages. Use + and − signs to indicate the location of charges. Explain in terms of the electron theory.

H. Where Are the Free Electrons on a Charged Body Located? Charge the insulated hollow sphere strongly by means of the electrophorous and test by bringing it near the electroscope. Also test by touching first the *outside* and then the *inside* of the charged sphere with the proof plane. Can you give an explanation in terms of the action between electrons? Charge

the egg-shaped conductor strongly. Lay the proof plane as flatly as possible against this body at various points and after each contact touch it to the uncharged electroscope. Where is the "surface density" of the charge greatest? Where would the *intensity of the electric field* around this body be greatest?

Set the wire-gauze cage over the electroscope and ground the former by touching it. Try the effect of moving the strongly charged plate of the electrophorus around in the neighborhood.

Exercise 36

MAGNETIC FIELDS

(Chapter XXXII)

The object of this experiment is to assist you in becoming more familiar with the various concepts which one meets in the study of fields of force and in particular with the concept of the magnetic field.

Apparatus.—A sheet of window glass 10 by 12 in.; two bar magnets; horseshoe magnet; bits of soft iron; iron filings in a saltshaker; six sheets of blueprint paper 8 by 12; small weights; arc light.

Place a glass plate over a bar magnet, lay a sheet of blueprint paper of the proper size over this and hold it in position by clips or by placing weights on the corners. It is important that it should lie smoothly. Sift iron filings evenly over the paper and tap the plate gently in order to allow the filings to arrange themselves under the action of the field. When you have secured a satisfactory pattern, carry the plate carefully to the arc light or window for exposure. Before exposing the prepared pattern it is best to make a series of trial exposures to determine the time required for a good print. This is best done by taking a narrow (1-in.) strip of the blueprint paper about 6 in. long and placing it in a book so that about 1 in. is exposed. Put this in position and after 1 min. pull the strip out so as to add another inch to the exposed part. Repeat until the whole strip is exposed. Remove and immerse in cold water for a few minutes. Decide as to the time which seems to give the brightest, clearest blue and make your exposures with the aim of securing this. In developing it is best to leave the prints in cold, running water at least 10 min.

Make other combinations of magnetic fields showing the field between like poles, that between unlike poles, the effect of soft iron in the field, and special forms of magnets.

In preparing your report be sure to give definitions of unit magnetic poles and unit field. Mark any neutral points (*i.e.*, points of zero intensity) found, and explain.

Glass belongs to the group of materials which are classed as *diamagnetic*. Why could not a thin iron plate be used instead of the glass?

The blueprint paper should be kept covered except while the fields are being obtained, and used in a part of the room away from direct sunlight or even too close proximity to a window. It is not very sensitive to ordinary light but "fogs" slowly and will then not give bright strong prints.

Exercise 37

ELECTRIC FIELDS

(Chapter XXXI)

Apparatus.—Static machine, several pieces of sheet metal or tin foil; wire or chain; a glass plate 10 by 12 in.; finely clipped hair in a shaker; several sheets of blueprint paper 10 by 12 in.

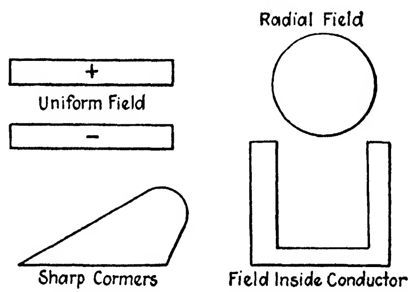


Fig. 40.—Some shapes which give interesting electric fields. They may be cut from tin foil but heavier material is better since it is important that they lie flat on the paper.

Arrange a sheet of blueprint paper as for a magnetic field but instead of putting magnets under the paper lay two pieces of any metal on the paper and connect each piece of metal to one terminal of the static machine. When the metal terminals are well charged sift finely clipped hair between them and note the result. It is usually useless to tap the plate as was done in the magnetic

case since the bits of hair stick to the paper and will not rearrange themselves. If a good pattern is not obtained at first trial, shake off the clippings and try again. Get good blueprints showing a uniform field, the field about a circular bit of metal, the field about a triangle which has had one angle rounded off, and other combinations. Why do sharp points tend to cause the discharge of electrification? Define the electrostatic unit of quantity of electricity and that of intensity of electric field.

Exercise 38

FURTHER STUDY OF MAGNETIC FIELDS

Comparison of Magnetic Moments

(Pages 315–318)

Apparatus.—Magnetometer, two bar magnets, horseshoe magnet.

The problem is to compare the magnetic moments of two small bar magnets and of a horseshoe magnet. The reason for doing this is that it offers an opportunity to do some rather simple work which involves thinking about the quantitative relations of a magnetic field.

The magnetic moment of a magnet is defined as equal to the couple which the magnet would experience if placed in a uniform field of unit intensity, with the line joining its poles (the axis of the magnet) at right angles to the direction of the field. (This assumes that the field would not be changed by the introduction of the magnet.) It may also be defined as the product of the pole strength times the distance between poles but, since the poles are not located at definite points, this does not lead to any convenient method of measurement.

The method used in the experiment is to compare the field produced at a point some little distance away from the magnet with the earth's magnetic field; or rather with the horizontal component of that field, since only this component is effective in determining the direction in which a compass needle points.

A magnetometer (Fig. 41) is simply a compass having a short needle to which a pointer is attached. In the case of the instrument furnished for this experiment the compass is mounted in the middle of a board which is provided with a meter scale and a groove along which the magnet under test is moved.

The first step is to set the magnetometer in such a position that the groove is at right angles to the needle. This may be done approximately by simple inspection. A more accurate adjustment is then obtained by putting one of the small magnets 20 cm. away on one side of the compass, noting the deflection; and repeating with the magnet the same distance away on the other side but turned so as to cause a deflection in the same direction. If the adjustment is right the two deflections will be equal. If they are not, swing the board slightly and repeat the test. Be sure that all other magnets are at a considerable distance away during this operation as well as during all other parts of the experiment.

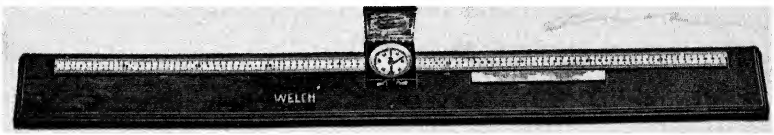


FIG. 41.—Magnetometer.

Now place the first magnet to be tested with its midpoint at a distance of 40 cm. from the support of the compass needle and note the deflection; turn the magnet around so that the other pole points inward and repeat. Move the magnet to the other side of the compass and make two more observations. Repeat all observations with the magnet 30 cm. and 20 cm. from the compass.

It is known that the field at a distance d from the midpoint of a magnet of length l and on the axis of the magnet extended is given by the equation

$$H_m = \frac{2Md}{\left(d^2 - \frac{l^2}{4}\right)^2},$$

where M is the magnetic moment of the magnet (see Problem 4, p. 318, text).

Designating the earth's field (horizontal component) by H_e and remembering that magnetic field intensity is a vector quantity one may easily show that

$$H_m = H_e \tan \Theta,$$

where Θ is the angle through which the compass needle is deflected as a result of the presence of the magnet when arranged as above.

By substituting this value of H_m in the previous equations and solving for M one finds that

$$M = H_e \cdot \left(\frac{d^2 - \frac{e^2}{4}}{2d} \right) \tan \Theta$$

(Fig. 42).

Now substitute the second small bar magnet and repeat all observations. The field due to the second magnet in any position is $H_m' = H_e \tan \Theta'$ and since Θ and Θ' have been measured for three positions of the magnets one may obtain three values for both M and M' in terms of H_e. How do the three values compare with one another for each magnet?

Replace the bar magnets by the horseshoe magnet and determine its magnetic moment in terms of H_e.

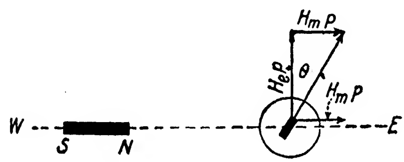


FIG. 42.

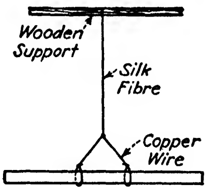


FIG. 42a.—Sketch, magnet to be supported symmetrically.

The horizontal component of the intensity of the earth's field may be measured in several ways one of which involves an extension of work with one of the bar magnets so far used. If one of these is placed in a suitable support and suspended by a torsionless fibre such as may be obtained by untwisting a bit of silk thread (Fig. 42a) the only restoring torque acting upon it when turned out of the magnetic meridian will be that due to the horizontal component of the earth's field. It is shown on page 315 of the text that the magnitude of this couple (L) is given by the equation

$$L = MH_e \sin \Theta.$$

It follows that such a suspended magnet will vibrate with angular s.h.m. if given a small displacement; and, by a method similar to that on page 254 of the text it may be shown that the period of vibration (T) is

$$T = 2\pi \sqrt{\frac{I}{MH_e}}$$

where I is the moment of inertia of the magnet. The value of I can be calculated from a knowledge of the weight and dimensions of the magnet by using one of the formulae given on page 105 of the text. The period T can be obtained by timing a number of savings with a stop watch and both M and H_e can then be computed by combining the equation for the period with that for the magnetic moment obtained above. If time permits the value of H_e should be obtained in this manner. Otherwise it may be obtained from the instructor and the magnetic moments of the three magnets computed. The distance between poles is somewhat uncertain and depends upon the dimensions of the magnet and the degree of magnetization in rather a complex way. For such bar magnets as are usually used it will not be far wrong to take it as three-fourths of the over-all length of the magnet.

Assuming this to be true, compute the pole strength of the two bar magnets used.

GROUP IX

ELECTRIC CURRENTS

Exercise 39

FUNDAMENTAL RELATIONS OF ELECTRIC CURRENTS

(Chapters XXXIII, XXXIV)

You are to make an experimental study of the relations between the electric current, the difference of potential (electric pressure) and the resistance of the circuit. Your text gives you certain *legal* definitions for units in which these quantities are measured. These definitions are in terms of certain standards. In a laboratory the standards are divided into two types, primary and secondary. A primary standard is usually a high-priced piece of apparatus which is not used for measurement but for checking the secondary standards which are used for the direct comparison with the unknown quantities to be measured in the laboratory. The following experiments should accomplish two things: make the material of the text more real to you and acquaint you with some of the various methods for the comparison of these quantities.

Apparatus.—Six-volt storage cell, low-reading voltmeter, ammeter, variable resistance board containing 10 meters of iron wire, switch, lamp, heater, etc.

A. Fall of Potential along a Uniform Wire.—Connect the circuit shown in Fig. 43, leaving the switch open and one terminal of the voltmeter unconnected (but with a free wire long enough to reach to any part of the board) until the instructor has inspected and approved the set-up. Arrange all such circuits in an orderly way and make connections neatly so that the path of the current can be easily traced. Notice that the + terminal of the ammeter is connected to the + pole of the battery. Notice also the difference in the methods of connecting the ammeter and the voltmeter. These instruments are always connected as here shown. The switch and variable resistance are important elements of the circuit. After the set-up has been approved,

adjust the resistance to allow any convenient current to flow; hold the free voltmeter terminal in turn on each binding post of the board; and read the voltmeter for each position, estimating tenths of the smallest divisions. These readings should be made rapidly. If two people are working together, the observer and recorder should change places and repeat with some different

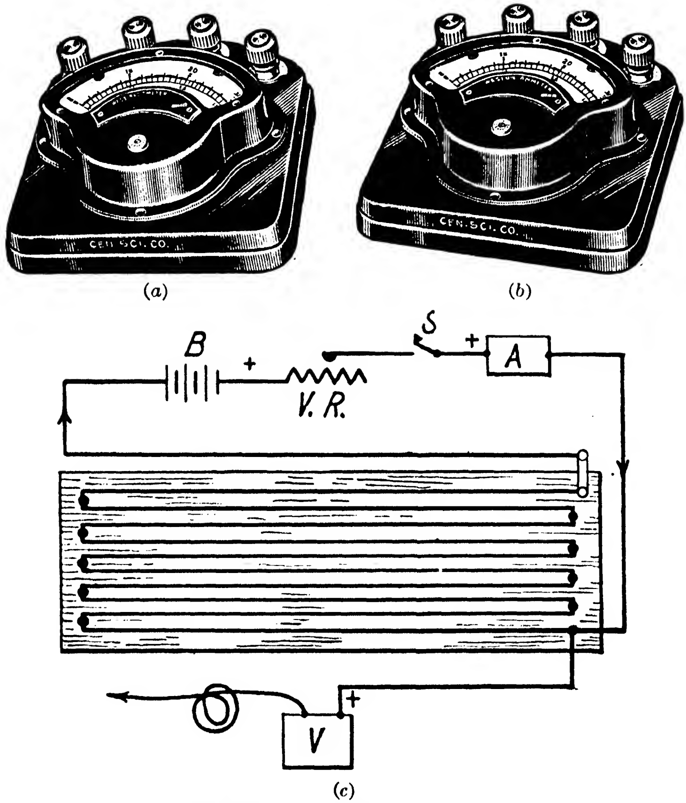


FIG. 43.—Diagram showing method of connecting an electric circuit containing an ammeter and voltmeter (*a*), voltmeter; (*b*), ammeter; (*c*), diagram.

value of the current. Plot a curve from these readings and in each case compute the ratio of the fall of potential to length of wire. What conclusion does this justify?

B. Variation of Fall of Potential with Value of the Current.—Change the connections on the board so that the current flows through only 1 or 2 meters of the wire. Adjust the variable resistance so that a current, as large as can be used without

heating the wire, may flow. Read the ammeter and determine the fall of potential across the part of the wire in use. Repeat for several other values of the current. Compute the value of the ratio E/I in each case. What is this called?

C. Use of the Voltmeter and Ammeter for Determining Resistance.—The above two experiments should, when their results are combined, lead to an experimental derivation of Ohm's law. Making use of this law and the voltmeter and ammeter, measure the resistance of several pieces of apparatus such as an electric lamp, heater, soldering iron, etc.

Exercise 40

THE ACCURATE COMPARISON OF RESISTANCES.

WHEATSTONE'S BRIDGE—SLIDE-WIRE FORM

(Chapter XXXIV)

Apparatus.—Resistance box, slide wire, dry cell, galvanommeter, single-throw switch, several known resistances, wires for testing, micrometer.

Before beginning this exercise, read carefully the whole of Chap. XXXIV and particularly that section which deals with the theory of the Wheatstone's bridge.

Set up the bridge as shown in the diagram (Fig. 44) and compare this with the bridge as discussed in the text. (Note that the two variable segments of the slide wire correspond to the ratio arms.) By means of the slide-wire bridge check the several known resistances against the resistance box. Always take such a resistance out of the box that the bridge is balanced with the slider near the middle of the wire. Why?

Arrange the several resistances in series and check the law of series resistances.

Arrange the known resistances to form as many divided circuit combinations as possible and check the laws of resistance of such circuits.

Determination of the Factors upon Which the Resistance of a Wire Depends.—You have a wire board containing several wires each 1 meter long. The wires in one group on this board are all of the same material but differ in diameter. Those on the other group are of different materials. Find the resistance of each wire by means of the slide-wire bridge. Make connections to the

board by short wide strips of sheet copper. Why? Is it true that for wire of the same material the resistance is inversely proportional to the cross-section of the wire? For each wire compute the ratio RA/L. What is this ratio called?

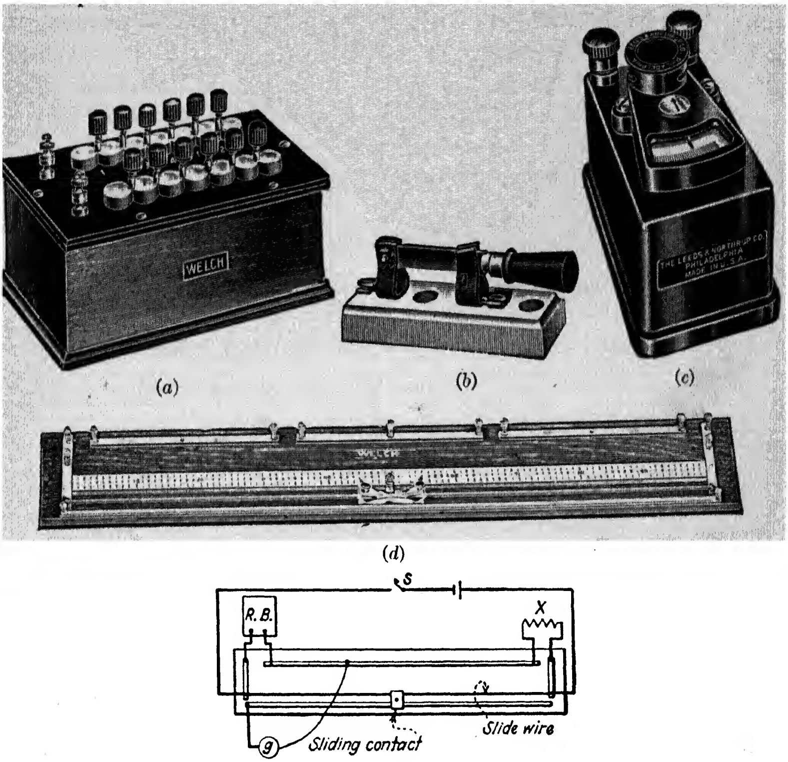


FIG. 44.—Apparatus and connections for Exercise 40; *a*, resistance box; *b*, single throw switch; *c* galvanometer; *d*, slide wire bridge; *e*, connections.

Exercise 41

THE DEPENDENCE OF RESISTANCE ON TEMPERATURE

(Page 333)

Apparatus.—Ammeter, voltmeter, two lamp sockets, tungsten and carbon lamps, rheostat, 110-volt direct-current source, box bridge, coil of wire immersed in oil, Bunsen burner, support, double-throw switch, thermometer 0° to 100° in degrees.

Set up the lamp circuit as shown in Fig. 45, adjust the variable resistance so that a current less than that required to light the lamps flows and measure the fall of potential across each lamp.

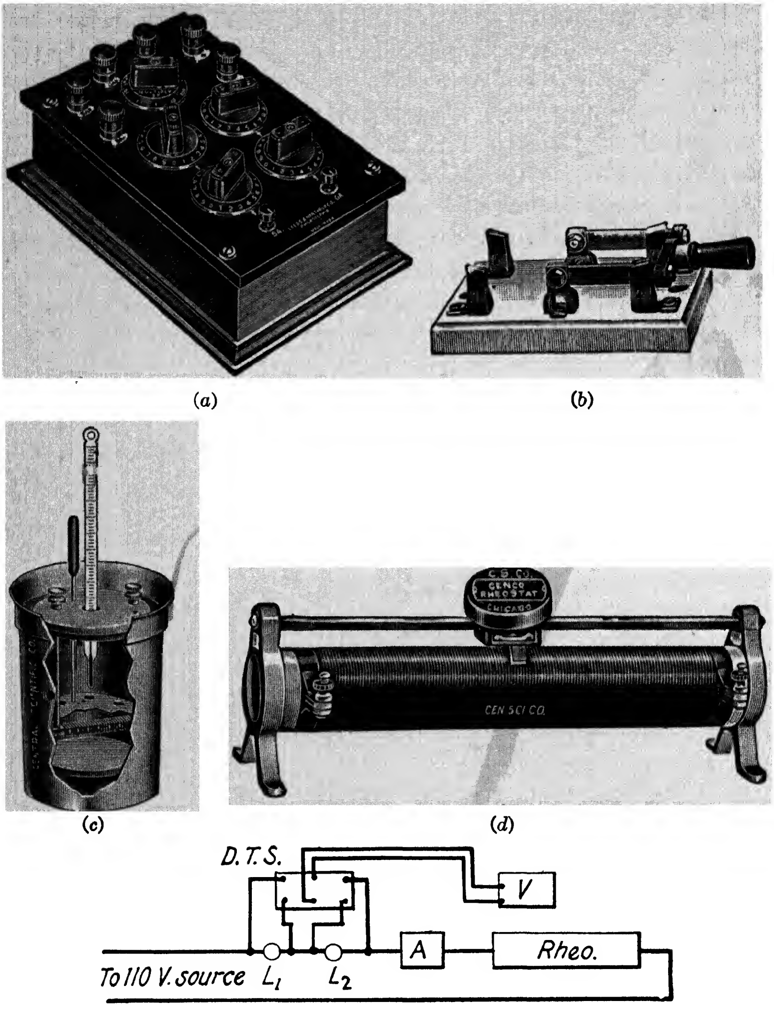


FIG. 45.—Apparatus and connections for Ex. 41; *a*, box bridge; *b*, double throw switch; *c*, calorimeter; *d*, variable resistance; *e*, connections.

Note that the double-throw switch enables you to change the voltmeter connections for this purpose without difficulty. Repeat for a number of increasing values of the current. Tabu-

late and compute the resistance of each lamp for each current value. Plot current-resistance curves for both lamps on the same sheet. Discuss.

The Temperature Coefficient of Resistance.—Set up the box bridge and resistance coil, making connections as indicated on the bridge. (The box bridge is a compact unit containing the three known resistances required for the Wheatstone's bridge network of conductors. It is the form always used in practice because of its greater convenience.) Pack the can containing the coil to be tested in ice and measure the resistance of the wire at 0°C. Raise the temperature by 10° steps and repeat. Be sure that the temperature has become constant at each halting place before the measurements are made and that the oil is thoroughly stirred. Plot the resistance-temperature curve and compute the mean temperature coefficient of resistance

$$\alpha = \frac{R_t - R_0}{R_0 \cdot \Delta t}$$

for the range covered. Compare with Handbook value.

Exercise 42

FARADAY'S LAW OF ELECTROLYSIS

(Chapter XXXIII)

1. When varying quantities of electricity pass through the same solution, the quantities of materials set free at either electrode are proportional to the quantities of electricity which have traversed the solution.

2. When the same quantity of electricity passes through several different solutions, the weights of the various materials liberated are directly proportional to their chemical equivalents.

This experiment offers an opportunity to make a quantitative test of the above laws and to become acquainted with the sort of evidence upon which they are based. It also offers an opportunity to become acquainted with a method of checking the accuracy of an ammeter.

Apparatus.—Copper voltameter, Hoffman's apparatus, low-reading ammeter, 20 per cent H_2SO_4 solution, copper-sulphate solution, 6-volt storage battery, rheostat, chemical balance, thermometer, barometer, hydrometer, single-throw switch, stop watch.

You are supplied with an apparatus for the electrolysis of water (Hoffman's apparatus) and with a small glass jar provided with covers so arranged that three copper plates can be attached to the cover. These vessels are usually known as "voltameters," a name which comes from the fact that current electricity was originally known as "voltaic electricity."

Procedure.—Connect the various parts of the circuit as shown in the diagram (Fig. 46), making sure that the middle plate of the

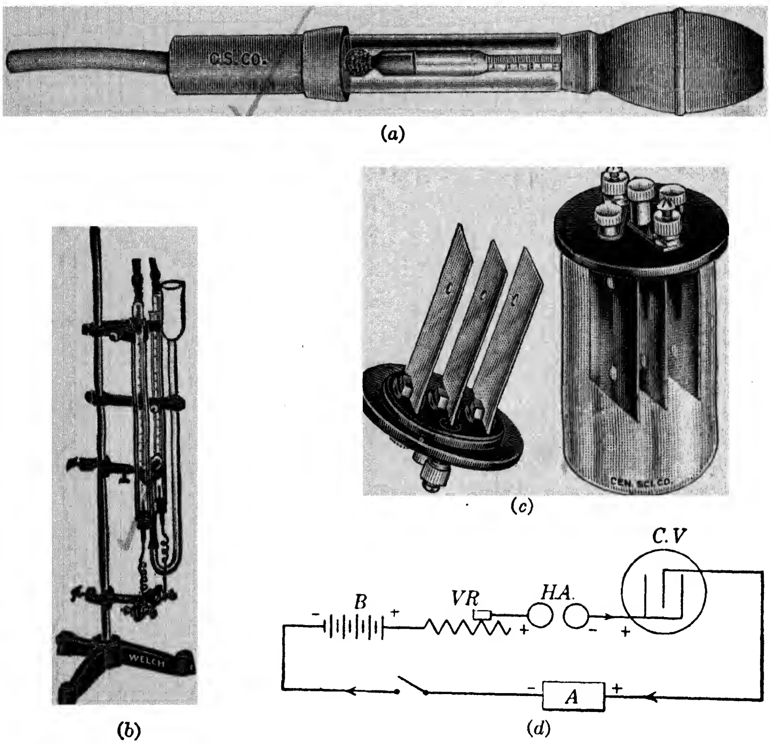


Fig. 46.—*a*, Hydrometer; *b*, Hoffman's apparatus; *c*, copper voltameter; *d*, diagram of connections.

voltameter is connected to the negative pole of the battery. When the connections are complete, close the circuit and by means of the variable resistance adjust the current to a value of about 0.15 amp. and allow it to flow for 2 or 3 min. in order to be sure that it remains steady and that everything is working properly. Any unsteadiness of the current will be due to a loose connection or a poor contact which must be found and corrected

during this preliminary period if satisfactory results are to be secured.

Break the circuit by opening the switch. Remove the copper voltameter and carry it to the sink without removing the cover.

Caution. *The copper sulphate used in the copper voltameter contains a large amount of sulphuric acid and will ruin a dress or suit if spilled on it.* Hence, these vessels must be handled with care and it is well to wear a laboratory coat or apron while working with them.

Remove the cover with the plates attached and wash the plates thoroughly in running water. When thoroughly washed, remove the middle plate from the voltameter and rinse quickly with wood alcohol to remove the water. In doing this be careful to handle the plate by the edges above the bright portion on which the deposition has occurred as a finger print is likely to make a spot to which the metal will not adhere firmly and thus ruin the results. Dry by holding above a Bunsen burner and show to the instructor. Particular care is required in drying the copper plate because wet copper oxidizes rapidly. Place in a desiccator as soon as dry. Weigh the plate on the chemical balance to the tenth of a milligram.

By opening the stopcocks, fill both arms of the Hoffman's apparatus.

Caution. *This liquid is a 20 per cent solution of sulphuric acid.*

Open the stopcocks slowly and carefully so that the liquid will not escape after the gas has been forced out. After handling this apparatus, wash your hands before touching anything else. Reassemble the apparatus and connect as before with the switch open. Close the switch and start the stop watch at the same instant. Read and record the current at the end of every minute for about 15 min. Estimate fractions of a scale division on the ammeter. Break the circuit and stop the watch at the end of the run. Perform the washing and drying operations as before and reweigh the cathode plate. Read from the Hoffman's apparatus the volumes of hydrogen and oxygen liberated. These volumes must be corrected for temperature and pressure and for this purpose the following observations will be required. Read the barometer to tenths of a millimeter and the temperature to tenths of a degree. With a ruler measure the difference in level between the solution in the reservoir and that in each arm of the Hoffman's

apparatus and determine the density of the solution by means of the battery hydrometer. **Remember the caution** previously given as to this solution.

If there is time for another run, return the plates to the voltameter and repeat. If the current has been found steady in the previous run it will be sufficient to make readings at intervals of 2 or 3 min. thus allowing time for some consideration of the previous results. Allow the current to run about twice as long in this case as in the first. At the end make the necessary observations and record.

The amounts of the metal deposited are obtained at once by subtraction. To find the quantities of hydrogen and oxygen it is necessary to reduce the observed volumes to those which the gases would occupy under standard conditions.

Obviously the gases are under pressures slightly greater than atmospheric, because of the weight of the liquid columns. These pressures, in grams per square centimeter, are equal to the heights of the columns multiplied by the density of the solution. In the present case it is more convenient to use as the unit of pressure that due to the weight of a column of mercury 1 cm. high and since the density of mercury is 13.6, the corrections for the columns (h_1 and h_2) are

$$c_1 = \frac{h_1 D}{13.6} \text{ and } c_2 = \frac{h_2 D}{13.6},$$

where D is the density of the solution as measured with the hydrometer. These corrections are to be added to the barometer reading to find the total pressure of the inclosed gases. This total pressure is in part due to the presence of water vapor in the tubes. To find the pressure exerted by the hydrogen or oxygen alone we must deduct that due to the water vapor. This can be found by looking in the "Handbook for Physics and Chemistry" (use the index under "vapor pressure"). Be sure that all these pressures are expressed in the same unit before combining them.

After the corrected pressure (*i.e.*, the pressure exerted by the dry gases) has been found, apply the general gas law to compute the volume which each gas would occupy under standard conditions; look up the density under these conditions (Handbook) and compute the weights of each element set free. From Faraday's second law it follows that, if the weight of each element deposited is divided by its chemical equivalent, the quotients should all be equal. Is this true? How can the first law be tested?

From the definition of a coulomb and Faraday's laws it follows that 96,540 coulombs of electricity must pass through a solution to liberate 1 g. equivalent of any element. Compute the number of coulombs which your experiment shows to have passed through each solution and compare the average of these with the result obtained by multiplying the ammeter reading by the time of the run in seconds. Is the ammeter reading correct? If not, what correction should be applied to readings in this range?

Exercise 43

THE HEAT EQUIVALENT OF ELECTRICAL ENERGY

(Page 327)

Apparatus.—Calorimeter with heating coil, thermometer (0° to 50° in $\frac{1}{10}$) stirrer, watch, ammeter, voltmeter, variable resistance, source of e.m.f.

Connect the apparatus as shown in Fig. 47, and adjust the variable resistance until a suitable current value is obtained. Remove the calorimeter and make the weighings necessary to determine the quantity of water used. Remember that it is best to fill with water below room temperature. Replace the calorimeter in the circuit and determine carefully the temperature and rate of change of temperature of the water. Close the circuit and at the same time start the stop watch.

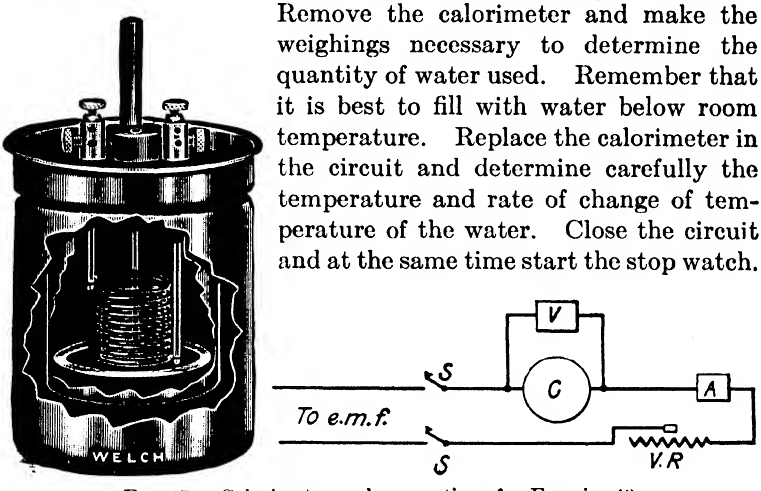


Fig. 47.—Calorimeter and connections for Exercise 43.

Keep the water thoroughly stirred and read temperatures at 1-min. intervals. Also read current and e.m.f. each minute. Continue until the temperature is about as far above that of the room as it originally was below. Open the switch (stop the watch at the same instant) but continue temperature readings until the final rate of change of temperature is well established. Make radia-

tion corrections and heat computations as previously directed (Exercise 19). Repeat, varying all conditions.

The input of electrical energy in *joules* is EIt which is to be compared with the heat developed to test the relation

$$H = 0.24EIt.$$

It is well to compare this experiment with that on the *mechanical equivalent of heat.* By analogy, what is the *electrical equivalent of heat?*

Instead of attempting to determine the heat capacity of the stirrer and its accessories it is better to eliminate the terms of the heat equation with which this quantity enters by comparing the results of the two runs. If M_1 and M_2 are the weights of the water in the two cases, C the heat capacity of the calorimeter, T_1 and T_2 the temperature changes, $E_1I_1t_1$ and $E_2I_2t_2$ the quantities of electrical energy used in the two cases, we may write

$$M_1T_1 + CT_1 = aE_1I_1t_1,$$
$$M_2T_2 + CT_2 = aE_2I_2t_2,$$

where a is the heat equivalent of electrical energy in calories per joule. Multiplying the first equation by T_2, the second by T_1, and subtracting, gives

$$(M_2 - M_1)T_1T_2 = a(E_2I_2t_2 - E_1I_1t_1),$$

or

$$a = \frac{(M_2 - M_1)T_2T_1}{E_2I_2t_2 - E_1I_1t_1}.$$

Exercise 44

ACCURATE MEASUREMENT OF POTENTIAL DIFFERENCE BY MEANS OF THE POTENTIOMETER AND STANDARD CELL[1]

(Chapter XXXIV)

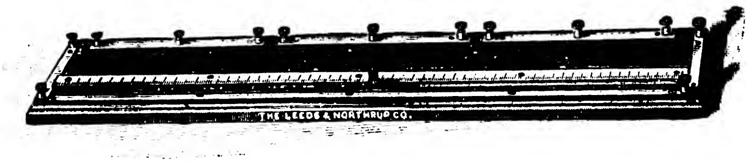
Apparatus.—Weston standard cell; several dry cells; 10,000-ohm resistance; galvanometer; slide wire, 1 meter long; preferably with resistance of about 10 ohms; variable resistance.

The Weston standard cell is one of the fundamental standards of electrical measurements. All electrical measurements and the calibration of all direct-reading instruments like ammeters and voltmeters depend upon the accurate comparison of other electro-

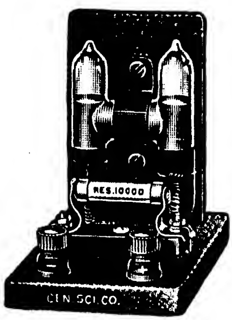
[1] This and Exercises 45 and 46 are closely related and should be completed in consecutive periods.

motive forces and potential differences with the difference of potential between the terminals of this cell when no current flows through it.

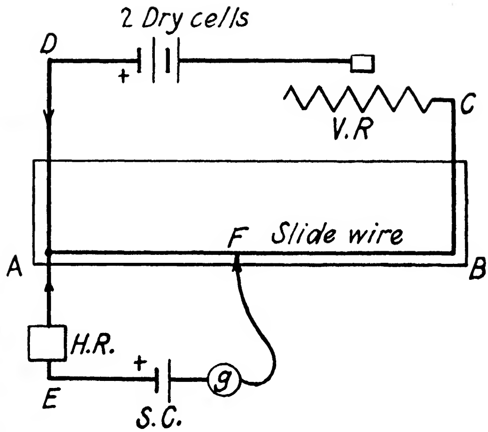
Instruments used for such comparisons are called "potentiometers." In addition these instruments are widely used where measurements of potential differences, currents or resistances of high accuracy are needed. A good potentiometer, a standard



(a)



(b)



(c)

FIG. 48.—Apparatus and connections for Exercise 44; (a) slide wire for potentiometer; b, Weston standard cell; c, connections.

cell, and a few standard resistances enable one to measure any one of the three fundamental electrical quantities easily and with great precision. It is the purpose of the following group of exercises to afford you an opportunity to become familiar with the principles involved and the methods used in such work.

In principle, all forms of the potentiometer are very simple. The fall of potential between the terminals of a variable resistance through which a constant current flows is, by adjusting the resistance, made to balance the potential difference of a standard cell and that to be measured in succession. Under these conditions, the two potential differences compared bear to one another

the same ratio as do the balancing resistances in the variable resistance. This will be more readily understood from the discussion of the simplest form of such an instrument and its auxiliary circuits.

In Fig. 48 the two circuits $ABCDA$ and $AEFA$ have the portion AF in common and the electromotive forces in these two circuits oppose one another at A. These are the essential features of all potentiometer arrangements. The upper circuit is first set up and the current in it adjusted by means of the variable resistance (V. R.). The only condition necessary as to the value of this current (the magnitude of which need not be known) is that the fall of potential in the resistance AB must be greater than the potential differences which are to be measured; but if this condition is not secured in the initial adjustment no harm will be done, since failure will be detected as soon as one starts measurement and the necessary readjustment can then be made. The lower circuit is next added. The high resistance (H. R.) is inserted to protect the standard cell and galvanometer against excessive currents during the process of adjustment and should be about 10,000 ohms. The important matter is to be sure that the standard cell (S. C.) is connected as shown.

When the circuits are completed proceed as follows:

a. Set the sliding contact F which moves along the wire AB as near A as possible and note the deflection of the galvanometer on closing the contact.

b. Move the slider F to the other end of the wire AB and again close and note the direction of the galvanometer deflection. If all is right in the circuit these two deflections will be in opposite directions. If this reversal is not obtained there are only two possible explanations. Either the standard cell is not correctly connected or the fall of potential in the wire AB is less than the e.m.f. of the standard cell, in which case the variable resistance (V. R.) must be reduced until a reversal is obtained. This process of testing the circuit should be the first step in the use of any potentiometer set-up. When a reversal is obtained the arrangement is ready to use.

c. Move the slider to a point near the middle of the wire AB and again note the direction of the galvanometer deflection. If the deflection is now the same as at A it is evident that the balance point lies to the right of the slider which should again be moved half way to B and the deflection again tested. Continue in this

way until a setting of the slider is found for which the galvanometer is only slightly deflected. If the method of halving the segment in which the balance point has been located is followed, not more than five trials will ever be needed to locate the approximate balance point, since in the most unfavorable case the fifth setting will be within less than 1 cm. of the point sought. (This assumes that the wire AB is 100 cm. long.)

When the balance point has been located with approximate accuracy as above, hold the key down and move the slider slowly in the required direction until the galvanometer shows no deflection. If the galvanometer is not very sensitive it may be best to remove (or short circuit) the high resistance (H. R.) during this final operation. Calling the resistance of the portion of the wire between A and the final position of the slider F, R_s and the e.m.f. of the standard cell E_s, it follows that

$$E_s = R_s I. \tag{1}$$

d. Replace the standard cell with the dry cell which is to be measured and repeat the operations described above. Calling the e.m.f. of this cell E_x and the resistance of the segment AF in this case R_x we have

$$E_x = R_x I. \tag{2}$$

Dividing equation (2) by equation (1) and cancelling we obtain

$$\frac{E_x}{E_s} = \frac{R_x}{R_s},$$

which is the relation stated above. Since the resistance of any two segments of a uniform wire are proportional to their lengths this may be written

$$E_x = E_s\left(\frac{R_x}{R_s}\right) = E_s\frac{L_x}{L_s},$$

where L_x and L_s are the lengths of the wire between A and the slider in the two cases.

It may, of course, happen that on testing out the set-up with the unknown cell it will be found necessary to readjust the current in the upper circuit. In this case it will be necessary to replace the standard cell, and relocate the balance for the new value of the current. Since the e.m.f. of a standard cell is rather low, it is best to make the original current adjustment so that the balance point for this cell will come near the middle of the wire.

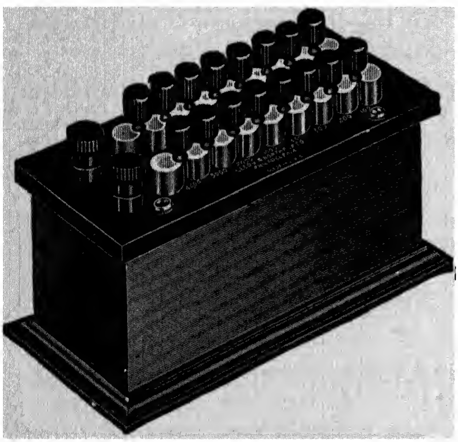
Determine the e.m.f. of the dry cell and mark this cell for use in Exercise 45.

Exercise 45

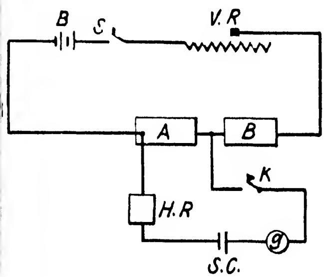
TWO-BOX POTENTIOMETER

Apparatus.—Two resistance boxes of the *plug-out* type standard cell, three dry cells, single-pole switch, key, galvanometer, 10,000-ohm resistance.

Since the resistance of the slide wire used in Exercise 44 is necessarily small and the current which it can carry is limited by the heating of the simple form of potentiometer described above,



(a)



(b)

FIG. 49.—Connections for two-box potentiometer. (*a*), resistance box, plug out type; *b*, diagram of connections.

it can be used only for measuring small e.m.fs. A somewhat less convenient arrangement allows for a practically unlimited extension of the range. In this arrangement, two exactly similar resistance boxes of the plug-out type take the place of the two segments of the wire, and the adjustment of resistances is made by transferring plugs from one box to the other, thus keeping the total resistance of the circuit constant. This arrangement is shown in Fig. 49.

Before completing the upper circuit, remove all the plugs (except the one marked *Inf.* which breaks the circuit inside the box) from box *B*. Test the direction of deflection under these conditions, then transfer the plug corresponding to the largest resistance

from *A* to the corresponding position in *B* and again test. Continue in this way with other resistances until the deflection is reversed, which shows that the resistance in *A* is too great. When this point is reached, return the last plug to *A* and try the next smaller resistance. Continue with each resistance in turn until a balance is obtained or until the changing of 1 ohm causes a reversal of the deflection.

It is, of course, necessary that the e.m.f. in the upper circuit be greater than that to be measured. Failure to get a reversal can only result from too low a value of this e.m.f. or from having the standard cell or unknown e.m.f. connected in the wrong direction. As in the previous exercise, it may be best to remove the protective high resistance while making the final adjustment in order to increase the sensitivity.

The quantitative relations are the same as in Exercise 44.

Redetermine the e.m.f. of the dry cell used in Exercise 44. What advantages and what disadvantages do each of these simple forms possess?

Exercise 46

TWO-BOX POTENTIOMETER WITH SLIDE WIRE

Apparatus.—22-volt B battery, one dry cell, three resistance boxes (two of plug-out type), slide wire having resistance of 1 ohm per meter, galvanometer, standard cell, two keys, 10,000-ohm resistance.

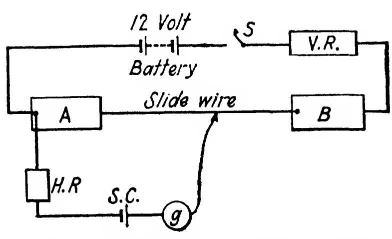


FIG. 50.—Combination of two box and slide wire potentiometers. (The connections between the boxes *A* and *B* and the slide wire must have a negligible resistance.)

The two forms of the potentiometer may be combined with advantage by inserting the slide wire between the two boxes and using it for the final adjustment. This secures the advantages of each of the simple forms without the limitations of either. If a slide wire having a resistance of 1 ohm per meter is available it is possible to make the instrument direct reading.

Set up the circuits as in Fig. 50. Remove all plugs from box *B* and then transfer from *A* to *B* until the resistance in *A* is 1,018

ohms and set the slide at the 30-cm. mark. Adjust the variable resistance (V.R.). (a resistance box similar to A and B should be used in this case) until there is no deflection of the galvanometer on closing the lower circuit. The current in the upper circuit is now exactly 1 milliampere (since $10183i = 1.0183$) so that, in the portion of the circuit including box A and the left-hand segment of the wire, there is a fall of potential of 1 millivolt (0.001 volt) per ohm. Hence the e.m.f. in the lower circuit may be found by balancing the circuit (using the slide wire for the final adjustment), writing down the value of this resistance and moving the decimal point three places to the left. If the resistance in the upper circuit is above 11,000 ohms the battery must have an e.m.f. of more than 11 volts to supply a current of 1 milliampere. Use a 12-volt battery.

Circuits like this but arranged for more convenient manipulation are extensively used in commercial potentiometers. Such an instrument will be used in the next exercise.

Exercise 47

USE OF POTENTIOMETER

The ordinary "potentiometer" of the laboratory is a self-contained unit equivalent to the arrangement of Exercise 46. Special forms of such instruments are usually accompanied by diagrams showing the connections. Such instruments are widely used because of their convenience and accuracy. It is the object of this exercise to illustrate some of the problems to which such a potentiometer together with its accessory apparatus may be applied in addition to the simple comparison of e.m.fs. previously illustrated.

Apparatus.—Potentiometer, standard cell, standard resistances, B battery, storage cell, unknown resistance, rheostat, double-throw switch, key, galvanometer, voltmeter.

A. Measurement of Currents.—The problem is to measure the current flowing in the circuit which contains the standard resistance and ammeter by means of the potentiometer and compare these values with the ammeter readings.

Set up the circuits as shown in Fig. 51. Connect the potentiometer as indicated by the symbols on the terminals of the instrument; turn the double-throw switch to connect the standard cell; set the potentiometer to read 1.0183; and adjust the current

in the dry cell circuit by means of the rheostat until closing the key causes no deflection of the galvanometer. This makes the instrument direct reading. It will be well to check the adjustment occasionally during the progress of the measurement. Next turn the double throw switch to substitute the fall of potential across the standard resistance for that of the standard cell and adjust the potentiometer setting until a balance is reached. Compute the current flowing in the ammeter circuit and compare with the ammeter reading. Change the current

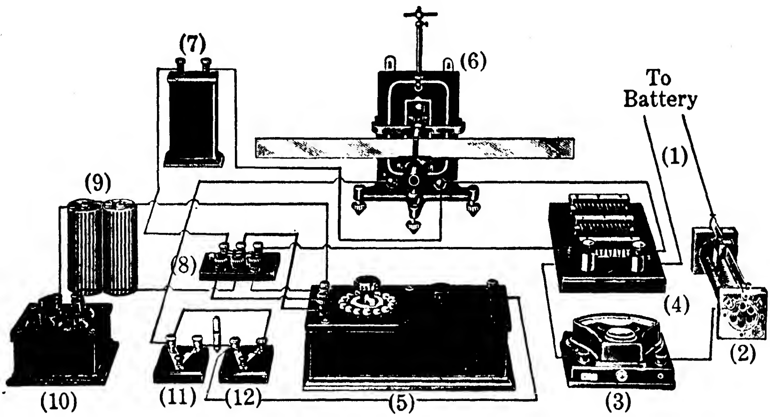


FIG. 51.—Apparatus and connections for Exercise 47 part A. (1) 6 volt storage battery, (2) variable resistance, (3) ammeter, (4) standard resistance, (5) potentiometer, (6) galvanometer, (7) standard cell, (8) double throw switch, (9) dry cells, (10) rheostat, (11, 12) single contact keys.

by means of the variable resistance and make several more determinations covering the range of the ammeter scale.

Plot a calibration curve for the ammeter, *i.e.*, ammeter readings as abscissæ and correct values as ordinates. Is any correction required for this instrument? If so how can it be most easily applied? Compare the accuracy of an ammeter and a potentiometer as a means of current measurement.

B. Devise a circuit in which an unknown resistance is to be measured by a somewhat similar procedure. Show diagram to the instructor and carry out the work.

C. Calibration of a Voltmeter.—Set up a circuit like Fig. 51*a*. Here the rheostat with the movable terminal forms a *potential divider*. From your previous work explain its operation. The process of calibrating the voltmeter consists in taking simultane-

ous readings of the voltmeter and of the potentiometer setting for various positions of the slider. For potential differences above 2.2 volts it is necessary to use a multiplier in connection with the potentiometer. This is a potential divider of fixed values so that a definite fraction ($1/50$ or $1/100$) of the potential difference at the

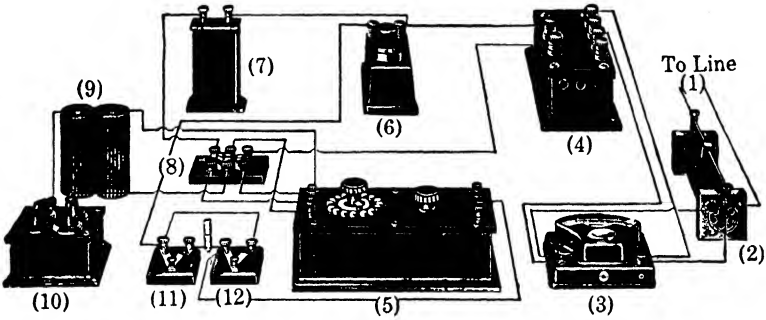


FIG. 51a.—Apparatus and connections for part c. (1) 110 volt leads, (2) potential divider, (3) voltmeter, (4) multipliers for potentiometers, (5) potentiometer, (6) galvanometer, (7) standard cell, (8) double throw switch, (9) dry cells, (10) rheostat, (11, 12) single contact keys.

voltmeter terminals is applied to the potentiometer. The potentiometer reading must then be multiplied by the proper factor. Make a set of observations covering the voltmeter scale and plot the calibration curve for the voltmeter (voltmeter readings as abscissæ and correct values as ordinates). Is any correction necessary? If so, what factor should be used?

Exercise 48

CALIBRATION OF A GALVANOMETER

(Pages 347–349, 358)

The suspended coil (D'Arsonval) galvanometer consists of a coil of fine wire of many turns suspended between the poles of a strong permanent magnet. An iron cylinder lying within the coil distorts the field between the magnetic poles so that it is nearly radial and of uniform intensity H close to the cylinder. As a result of this distribution, the couple acting on the coil when a current I flows through it is nearly uniform and equal to $HInA$ for all positions of the coil which give readable deflections (see p. 347, text). A voltmeter contains such a galvanometer unit in which the coil is suspended on jeweled bearings and con-

trolled by a spring which opposes the torque set up by the current. It is the purpose of this experiment to afford the student an opportunity to become familiar with the use of a sensitive galvanometer as a measuring instrument and to see how such an instrument might be converted into a direct-reading voltmeter by the addition of a suitable resistance in series with the coil or into an ammeter by the use of a shunt. Before beginning the experimental work ask the instructor to remove the cover from a wall galvanometer so that you may see its construction.

Apparatus.—D'Arsonval galvanometer, megohm box, resistance box, dry cell, potential divider, key.

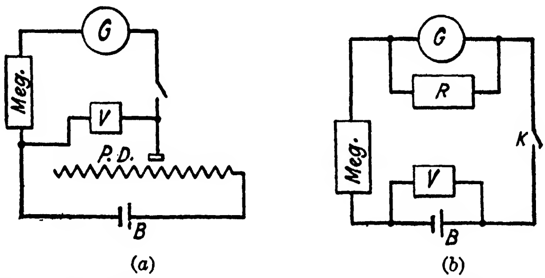


FIG. 52.—Circuits for galvanometer calibration; *a*, series; *b*, shunt.

A. Series Method. Theory of Voltmeter.—Connect the galvanometer, a single dry cell, a megohm box (ten 100,000-ohm coils) and a key in series. Adjust the galvanometer scale so that it reads zero when no current flows. Close the key and when the coils comes to rest read the amount of the deflection. If this is more than about 5 cm. the e.m.f. must be reduced either by the use of a potential divider or by connecting a used cell in opposition to a new one. With a voltmeter measure the fall of potential across the galvanometer and megohm box. When a satisfactory deflection has been reached, record it, change the connections so as to reduce the resistance by 100,000 ohms and repeat. Continue in this way until a deflection as large as can be read on the scale is obtained. Reverse the battery connections and repeat the reading on the other side of the scale.

Since all other resistances in the circuit are small in comparison with the resistance in the megohm box, this resistance alone enables one to compute the currents flowing in the circuit with sufficient accuracy. Compute the current corresponding to each deflection and plot a curve showing the relation between

currents and deflection. What current must flow through the coil to cause a deflection of one division? What resistance would it be necessary to put in series with the galvanometer in order that it might be used as a direct-reading millivoltmeter; *i.e.*, indicate 1 millivolt per division? The galvanometer resistance is marked on the card attached to the instrument.

B. Shunt Method. Theory of Ammeter.—Connect a single dry cell in series with the galvanometer and the megohm box and adjust the resistance to give the maximum readable deflection. Also connect a resistance box (0 to 10,000 ohms) as a shunt between the galvanometer terminals. Starting with zero, increase the shunt resistance step by step until the maximum readable deflection is obtained. Compute the current through the galvanometer in each case and plot a curve of currents and deflections on the same sheet as above. Do the two curves agree? What would be the value of a shunt such that 1 milliampere of current in the main circuit would cause a galvanometer deflection of one scale division? In computing the currents it may be assumed that the total current remains constant. Why?

Exercise 49

THE MEASUREMENT OF QUANTITIES OF ELECTRICITY BY THE BALLISTIC GALVANOMETER. A STUDY OF CAPACITIES

(Page 356)

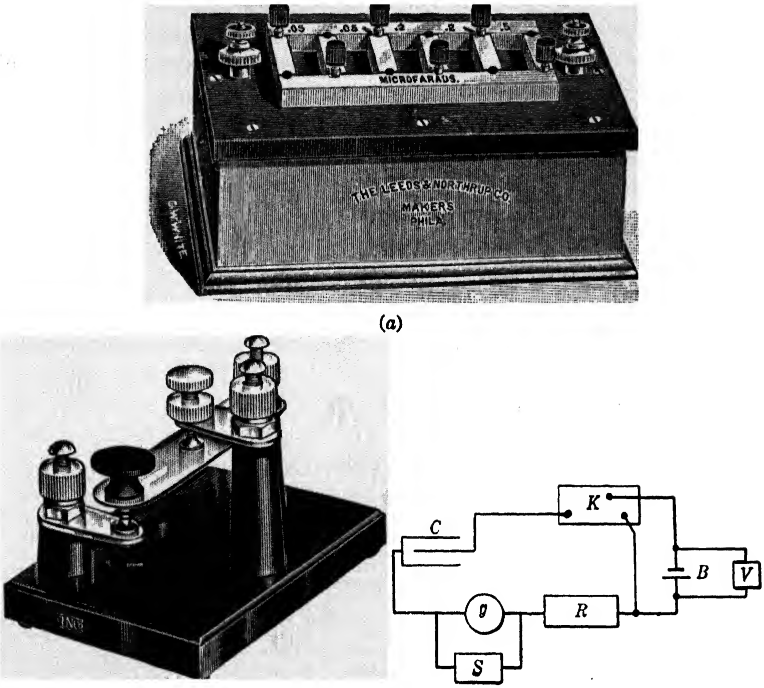
Apparatus.—Ballistic galvanometer, standard condenser, condensers of unknown capacity ($\frac{1}{10}$ to 1 mf.), key, resistance box, voltmeter, dry cells.

Measure the e.m.f. of the dry cells. (For very accurate work a potentiometer should be used instead of the voltmeter. Why?) Make connections as shown. Notice that the key is so connected that it may be used either to charge or to discharge the condenser through the galvanometer. If a variable standard condenser is used begin with a single dry cell and a capacity of 0.05 microfarad (1 mf. = 10^{-6} farad).

Break the circuit of the box S which shunts the galvanometer and charge the condenser. Notice that the galvanometer swings back and forth several times before coming to rest. Reconnect the shunt and remove a small resistance. In what two ways does this change the motion of the galvanometer? Explain. By

trial find what resistance must be removed from the shunt in order that the galvanometer will just return to the zero reading without delay and without oscillating. This is called the "critical damping resistance" and the galvanometer is most conveniently used when its coil is in series with such a resistance.

When the adjustment has been made, pass varying quantities of electricity through the galvanometer and note the throws



(a)

(b) (c)

Fig. 53.—Standard condenser, key, and diagram of connections for measuring capacities; *a*, condenser; *b*, key, *c*, diagram.

corresponding to each. In what two ways may the quantities of electricity be varied? Use both, tabulate all data and plot on the same sheet calibration curves for the charge and discharge of the galvanometer. If the two curves do not coincide explain why? Measure the capacities of each of the two or three unmarked condensers. Be sure that you clear up your ideas as to capacities, quantities of electricity, and units while working on this exercise. How could you use the ballistic galvanometer and a standard condenser to measure an unknown e.m.f.?

Exercise 50

MUTUAL INDUCTANCE—MEASUREMENT OF MAGNETIC FLUX LINKAGES

(Page 365)

Apparatus.—Toroid or long solenoid with primary and secondary windings (the latter divided into two equal parts) of known constants, ballistic galvanometer, rheostat, resistance box, key, 6-volt battery.

Connect the apparatus to form a *primary* and a *secondary* circuit as shown, with half the secondary coil in series with the galvanometer. Adjust the resistance in the secondary circuit so that when the current in the primary is broken the galvanometer coil just swings back to its position of rest without oscillation or delay (critical damping resistance, see Exercise 49).

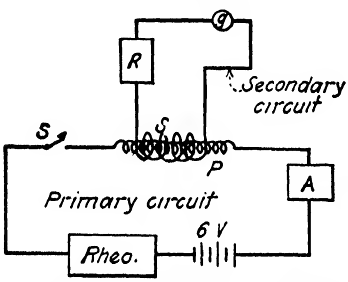


FIG. 54.—Calibrating a ballistic galvanometer as a flux meter.

Begin with a primary current such that breaking it causes a galvanometer throw of about 2 cm. and determine the throw on breaking the primary circuit for at least five different values of the primary current. Repeat, using twice as many turns on the secondary.

These results enable one to calibrate the galvanometer as a fluxmeter, *i.e.*, an instrument by means of which changes in flux linkage may be readily measured. This is one of the most fundamental of electromagnetic measurements. Plot curves for the two sets of data above, using primary currents as abscissæ and galvanometer throws as ordinates. What do these curves show as to the relation of throws to change in primary current for a given secondary? As to the relation of throws to the number of turns on the secondary for a given change in primary current?

The primary solenoid wound with n_1 turns per centimeter and carrying a current of I_1 abamperes produces within itself a magnetic field having an intensity of $4\pi n_1 I_1$ gauss (or lines per cm.^{2}). In the nonmagnetic material upon which this coil is wound the field intensity is numerically equal to the flux density

B (flux per cm.^{2}). The total flux φ through the solenoid is then equal to BA_1 where A_1 is the cross-sectional area of the primary coil. As arranged, all these lines link all turns of the secondary so that the flux linkages λ_2 for the secondary are equal to N_2BA_1. Since all these linkages disappear when the circuit is broken, we have

$$\Delta\lambda_2 = N_2\varphi_1 = 4\pi n_1 I_1 A_1 N_2$$

where N_2 is the *total* number of secondary windings.

The number of flux linkages in one of two coils produced by a current of 1 abampere in the other is defined as the *mutual inductance* of these coils and is measured in abhenries if one uses the electromagnetic system. An abhenry is evidently exactly one linkage. In the practical system the mutual inductance (M) is measured in *henries*. A henry is 10^8 abhenries or 10^8 linkages per ampere so that for the practical system,

$$M = \frac{N_2\varphi_1}{10^8 I_1} = \frac{4\pi n_1 A_1 N_2}{10^8}.$$

Compute the mutual inductance of the coils used in henries.

Lenz's Law.—Note carefully the direction of the primary and secondary windings and the direction of the primary current so that you can determine the direction of the primary flux. To determine the direction of the secondary current proceed as follows: Connect one terminal of a dry cell to the galvanometer, hold the other connected to the other terminal between your thumb and forefinger and touch the tip of your finger to the other galvanometer terminal. (The finger tip serves as a high resistance to protect the galvanometer.) From the direction of the galvanometer throws determine the direction of the current in the secondary coil and hence the direction of the temporary flux produced by it. Does this agree with Lenz's law?

Exercise 51

THE SIMPLE DYNAMO

Apparatus.—Simple dynamo (magneto), ballistic vanometers, and resistance box.

The apparatus is shown in Fig. 55. A coil of wire is placed in a uniform magnetic field and arrangement made so that this coil may be caused to rotate by 15° steps. If the coil is connected to a ballistic galvanometer, the throws of the latter are propor-

tional to the total quantity of the electricity passing through it and hence to the average value of the e.m.f. generated during the short time interval required for the motions of the coil. Connect the coil and the galvanometer in series and not the deflection obtained when the coil moves 15° from the position in which it incloses the least flux. If the throw is too large (off the scale), reduce the sensitivity of the galvanometer by shunting it with a suitable resistance.

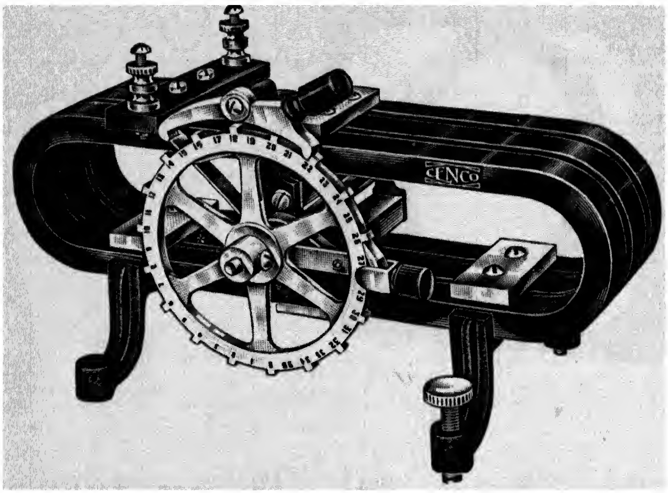


FIG. 55.

Record galvanometer throws for three complete revolutions of the coil and plot coil positions and throws. What does the curve show? In your report explain clearly the relations between the flux changes, the e.m.f., and the galvanometer deflections. Upon what does the current through the galvanometer at any instant depend? In what ways is an actual dynamo different from this magneto? Does this device produce a direct or an alternating e.m.f.? In general make your report a short essay on "Dynamos."

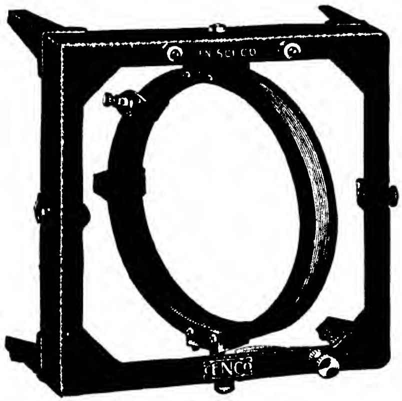
Exercise 52

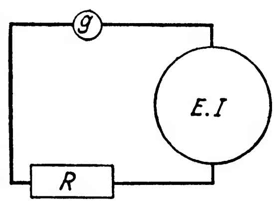
MEASUREMENT OF THE EARTH'S MAGNETIC FIELD

(Pages 316, 356–359)

Apparatus.—Calibrated ballistic galvanometer, earth inductor.

Use the ballistic galvanometer calibrated in the previous exercise. Connect the earth inductor coil, the resistance box and galvanometer in series and adjust to the critically damped condition. Set the inductor coil to rotate about a vertical axis and with its plane nearly east and west. Set the spring, release, and note the galvanometer throw. Repeat twice and take average. Rotate the whole apparatus about 5 deg. in either direction about a vertical axis and repeat. If the throw is increased, turn the coil about as much more in the same direction and repeat the readings. If the throw is decreased, rotate in the opposite direction. Continue in this way until the deflection reaches a maximum and begins to decrease. Locate the position of maximum deflection as accurately as possible and make five or more determinations of the throw in this case. From the curve of the previous exercise and the known constant of the coil determine the flux density of the horizontal component H of the earth's field.





(a) (b)

FIG. 56.—Earth inductor and diagram of connections. a, inductor; b, connections.

Next, turn the coil so that its axis is horizontal and take several throws with the axis pointing in different directions. Compute the vertical component (V) of the earth's field from these observations.

These are the horizontal and vertical components of a field F having a magnitude $F = \sqrt{H^2 + V^2}$, and a direction such that $V/H = \tan \Theta$ where Θ is the angle of dip; *i.e.*, the angle which the direction of the earth's field makes with the horizontal.

Turn the coil into position with its plane perpendicular to the computed direction of the resultant field and determine the value of that field. Compare with the computed value as a

check. (Be sure that you actually get the position of maximum throw.)

Make your report a short essay on the earth's magnetic field using your data as illustrative material.

Exercise 53

THE EFFECTS OF INDUCTANCE IN ALTERNATING-CURRENT CIRCUITS

(Chapter XXXVIII)

Apparatus.—Alternating-current voltmeter, alternating-current ammeter, wattmeter, large solenoid of several hundred turns with center tap and overall resistance of about 5 ohms, iron core, rheostat, lamp.

Measure the resistance between the terminals a and b, and a and c of the large solenoid by the voltmeter-ammeter method using direct current. Connect the whole coil in series with a suitable rheostat to 110-volt, 60-cycle, alternating-current mains including an incandescent lamp in the circuit, and note both the current (alternating) and the fall of potential across the coil. Explain fully why the ratio I/E thus obtained is less than that when direct current is used. Without breaking the circuit, insert an iron core in the solenoid and note the effect. Repeat, using the connections which give half the number of turns. From the equation,

$$E = I\sqrt{R^2 + (2\pi fL)^2},$$

compute the value of *the inductance L* in each case. How does the inductance of a solenoid depend upon the number of turns on it? Explain the effect of the iron core. Is the inductance constant for all current values (a) when no core is used? (b) when an iron core is used? Explain. Use a wide range of current values in testing this point and explain any results of interest.

Power Factor.—Connect the solenoid (air core) as shown and read the ammeter, voltmeter, and wattmeter for each of several current values. How does the power read from the wattmeter compare with the product EI (called "voltamperes")? The wattmeter consists of two coils one of which, the volt coil, rotates in the field produced by the other (the current coil). Since the strength of the field is at every instant proportional to the current flowing *in* the solenoid and the current in the volt coil

proportional to the fall of potential *across* the solenoid, the torque at any instant is proportional to the product of the instantaneous values of current i and fall of potential e. (Note use of small letters to denote instantaneous values.) It can be shown that under these conditions the wattmeter needle, being far too sluggish to follow the rapid variations in the torque, is deflected by an amount proportional to the *average* of the product ei taken over a full cycle so that if properly calibrated it indicates the true power absorbed in the solenoid.

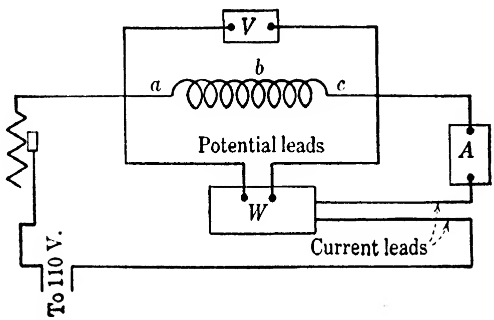


FIG. 57.—Diagram for wattmeter connections.

The ratio $\frac{\text{true power}}{\text{voltamperes}}$ is called the "power factor" of the circuit since it is the factor by which the product EI must be multiplied to give the true power.

Repeat, with the iron core in place. What effect is produced upon the power factor of a circuit of constant resistance by increasing the inductance? Is there any relation between the power factor in each of these cases and the value of the ratio

$$\frac{R}{\sqrt{R^2 + (2\pi fL)^2}}$$

in the corresponding case?

Draw a vector diagram (text, p. 393, Figs. 20 and 21) for each of your circuits. What is the *angle* of lag in each case? How is this related to the power factor? Draw the sine curves for the current through the solenoid and the fall of potential across it in the case having the *smallest* power factor.

Exercise 54

CHARACTERISTIC CURVES OF A VACUUM TUBE

(Pages 402–407)

Apparatus.—UX 201-A tube, milliammeter (0–20 m.a.), voltmeter (0–80 volts), potential divider (commonly called a potentiometer) of 2,000 ohms resistance or greater, voltmeter (0–30 volts), B battery of 100 volts, C battery of 45 volts, tube socket and 20-ohm rheostat, 6-volt storage battery, and 6-volt voltmeter.

Connect apparatus as in the diagram Fig. 58. *P-Q* is the potential divider, the midpoint of which is connected to the grid of the

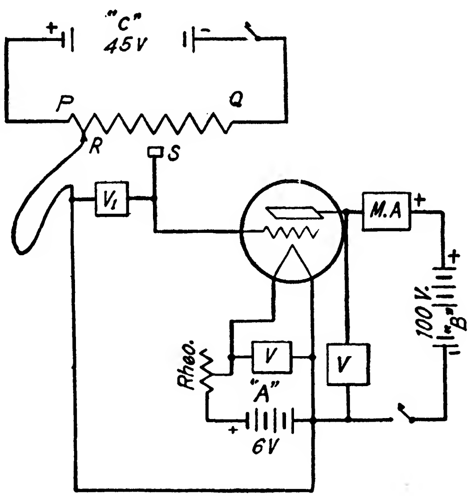


Fig. 58.

tube and to the low-range voltmeter. The plate of the tube is connected to the + side of the other voltmeter and to the − side of the milliammeter the + side of which is connected to the B battery. Connect the A battery as shown and adjust the rheostat until there is a drop of exactly 5 volts across the filament of the tube. Never let the drop across the filament vary from this value during the experiment. The negative terminal of the A battery is connected to the grid voltmeter V_1 and to a free wire (labeled *R*) which may be connected to either *P* or *Q*. Take some convenient B-battery tap, say 90 volts, and connect

point R to point P, and point S to Q. There is now a negative bias on the grid equal to the IR drop along PS which is read by the voltmeter V_1. (This means that the grid is charged to a *negative* potential of V_1 volts with respect to the filament. How will this effect the electrons emitted by the filament?) By movement of point S you can make this negative bias anything from 0 to 45 volt. Start with it at point P and move it at intervals of 0.5 volt taking each time the voltmeter reading and the reading of the milliammeter. Continue until the reading of the milliammeter is brought to zero. Now connect point R to point Q (you will have to reverse the leads of the voltmeter) and repeat the process. You now have a positive bias on the grid and the milliammeter should show an increased plate current. Adjust point S at intervals of 1 volt until you have the largest positive bias that the voltmeter will read. Tabulate your results and plot a curve with plate current as ordinates and grid voltage as abscissæ as the readings are taken. Repeat with other values of the B battery. Make your report a short essay on vacuum tubes using your results as illustrative material.

Exercise 55

EFFICIENCY OF AN ELECTRIC MOTOR

Apparatus.—Small variable speed direct-current motor (1/16 h.p. or greater), voltmeter and ammeter of suitable range, rheostat, stand, two spring balances, of suitable range, a belt to go around pulley of motor and attached to spring balances, revolution counter and watch, calipers.

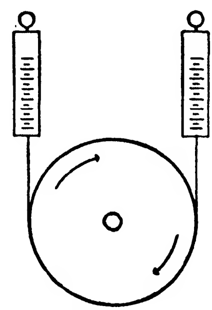


FIG. 59.—A simple friction brake for measuring the work done by a rotating pulley.

Read Chap. IV of text. Arrange the brake as in the diagram. Place belt around pulley and connect the ends to the spring balances which hang from the stand. To start the experiment adjust the balances so that the friction is great enough to keep the motor from running. This may be accomplished by raising the support. Close the motor switch for *an instant* and take ammeter and voltmeter readings. *Do not allow the motor to remain in this condition for more than a few seconds as it will burn out.* This operation

should be done very quickly and then the tension released so that the motor will run slowly. Take the number of revolutions in 2 or 3 min. and reduce to the number per second. Read the ammeter, voltmeter, and balances. Repeat for eight or ten different speeds gradually lessening the tension in the balances until the motor runs freely. Measure the diameter of the pulley with the calipers. Reduce the readings of the balances to dynes and compute the number of joules of work per second that the motor is delivering. Your ammeter and voltmeter readings will enable you to compute the input in joules per second. Plot a curve showing the efficiency of the motor as a function of the number of revolutions per second. Since the efficiency is zero both when the motor is running idly and when it cannot move, as in the first instance, there must be a speed at which the motor runs most efficiently. Determine this speed from your graph. Derive in detail the equations you use in your calculations.

GROUP X

SIMPLE OPTICAL EXPERIMENTS

Exercise 56

A STUDY OF SPECTRA

(Chapter XLI)

Apparatus.—Simple grating spectroscope with replica grating (Fig. 60); incandescent lamp; spectrum tubes of various gases; Bunsen burner; NaCl, LiCl, SrCl, $CaCl_2$; small strips of asbestos; mirrors.

FIG. 60.—Simple spectroscope.

Continuous Spectrum.—Set the incandescent lamp behind the slit. How many bands of color can be seen? How are the colors arranged? What are their "short" and "long" limits as read on the scale? If convenient to put a rheostat in series with the lamp note the effect on the spectrum of increasing or decreasing the temperature of the filament. Is the whole spectrum brightened to an equal degree by an increase in temperature?

Bright-line Spectra.—Use a Bunsen flame colored by (*a*) sodium, (*b*) lithium, (*c*) strontium, (*d*) calcium. Use these in the form of the chlorides and wet the calcium with dilute hydrochloric acid. Record the position and color of each line seen. Also use such spectrum tubes as are available; hydrogen and helium are particularly interesting. With hydrogen note the spacing and the relative intensities of the lines (text, pp. 426 and 603).

Solar Spectrum.—By means of the mirrors throw an image of the sun on the slit (for this purpose the slit must be closed until very narrow). Note the positions of any particularly strong dark lines.

These observations are chiefly valuable upon the qualitative rather than the quantitative side. That is, it is of far more importance that you learn what the various types of spectra *look like* than that you measure "wave lengths." Among other things try to acquire some feeling of the relation between wave length and color so that you can at least approximately translate a description in terms of color into wave lengths. For example, what lengths correspond to *green?*

Your report should be a short essay on *spectra* using your observations as illustrative material.

Exercise 57

A COMPARISON OF THE LIGHTING EFFICIENCY OF SEVERAL TYPES OF ELECTRIC LAMPS

(Pages 449–451)

Apparatus.—Student's optical bench; photometer; standard lamp; gas-filled, vacuum, and carbon lamps; ammeter; voltmeter; four-pole double-throw switch; two rheostats; source of current (110 volts, direct current). (NOTE.—If 110 volt direct current is not available, the experiment may be conveniently modified by using automobile light globes and a 6-volt battery.)

Three types of incandescent lamps have followed one another in the history of electric lighting. In the earliest, a carbon filament inclosed in a vacuum was heated by the passage of the current. In the second, the carbon filament was replaced by a fine metallic wire, also in a vacuum; while in the third (the one

now in general use), the wire (tungsten) is surrounded by an inert gas (nitrogen or argon). Each change has been accompanied by greatly increased efficiency with resulting decrease in the cost per unit of illumination. It is the purpose of this experiment to compare these three types of lamps.

Instruments used in comparing light efficiencies are called "photometers." The type commonly used in the elementary

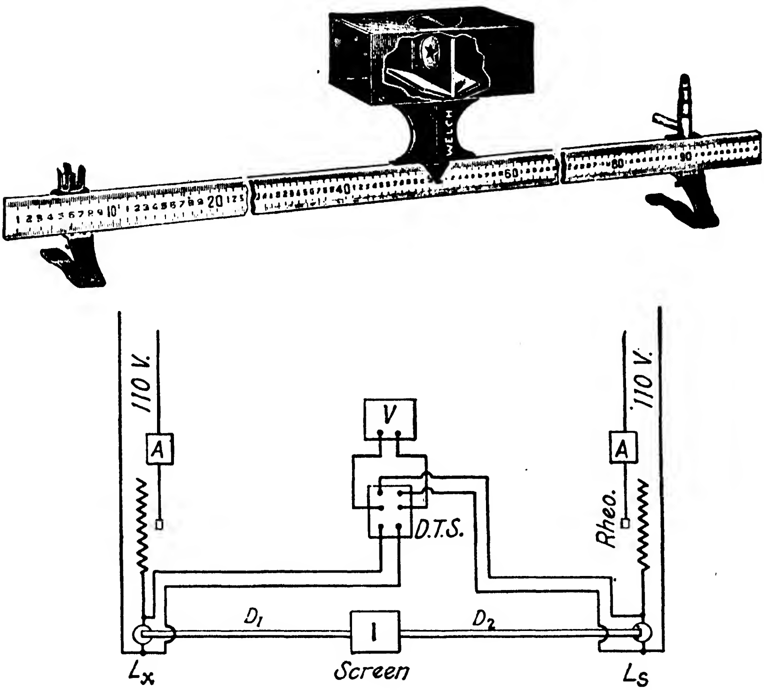


FIG. 61.—Photometer and diagram of electrical connections for Exercise 31.

laboratory is the Bunsen or "grease-spot" photometer. This instrument consists of a circular piece of white paper with a translucent center (the grease spot). Mirrors are so placed that one sees both sides of the screen at the same time; and the whole apparatus is moved back and forth in the line between two light sources until the spot, as seen on the two sides, contrasts equally with the rest of the screen. In the ideal case it would disappear completely but this condition is seldom attained.

Set up the apparatus as shown in the diagram, with the lamps 200 cm. apart. Adjust the rheostat in series with the standard

lamp until the fall of potential across this lamp is exactly that marked on it. (Approach this setting from the low potential side and be careful that the drop across the standard lamp never exceeds its rated value.) Throw the double-throw switch to the other socket and with the gas-filled tungsten lamp in position, adjust the control rheostat until the potential difference is exactly the rated voltage for this lamp. Move the screen back and forth and note carefully the changes in appearance before attempting any readings.

Settings are best made as follows: Starting with the screen in a position where the two sides are quite unequally illuminated, move it steadily and rather rapidly in the required direction until equality appears to be attained. Read this setting and repeat twice from the same side, then three times from the other side and take the average of all settings. It is very little use to spend much time in each setting: eyestrain and mental indecision play a larger part the longer one spends on each setting. The whole process of making a setting and reading the position of the screen should not occupy over half a minute. Repeat and compare the average of one series with that of the other. Repeat for 20, 15, 10, and 5 volts below and 5 volts above the rated voltage of the test lamp. Substitute the metallic, vacuum lamp and the carbon filament lamp in turn and repeat all settings. It is shown in the text that the candlepowers of two lights which produce equal illumination on a screen are directly proportional to the squares of their distances from the screen; *i.e.*, in case the unknown lamp is at zero and the standard at 200

$$\frac{P_x}{P_s} = \frac{D_x^2}{D_s^2} = \frac{D_x^2}{(200 - D_x)^2}.$$

On a single sheet plot curves showing the power of each lamp as a function of the potential difference across it and compare one lamp with another in this respect. On a second sheet plot for each lamp, the *luminous efficiency* (candlepower per watt) as a function of the terminal voltage and compare.

A house is lighted by ten 60-watt gas-filled lamps which burn on the average of 3 hours per day. Compute the lighting cost *for an equal amount of light* using each type of lamp if the rate is 5 cts. per kilowatt-hour (use the efficiency curves). Has the gas-filled lamp any obvious advantage, other than economy?

Exercise 58

THE LAW OF REFLECTION

(Pages 451–456)

Apparatus.—Drawing board, small mirror (½ by 2 in.), silvered on the front and mounted on a wooden back, 10 pins (those with spherical heads and about 1¾ in. long are best), T square, triangle, thumb tacks.

Fasten a sheet of paper to the board and draw a pair of intersecting perpendicular lines with the point of intersection near the center of the paper. Place the mirror in such a position that its reflecting surface coincides with one of these lines and set a pin upright on the other line about 3 in. in front of the mirror. Locate the line in which the image lies as seen from several different positions by placing two pins in line with the image as shown in the diagram. *If you wish good results, you must be careful to place all pins firmly in position and upright.*

Finally place a single pin at a point behind the mirror such that the portion of it seen by looking over the top of the mirror appears like an extension of the reflection of the original pin when viewed from any position.

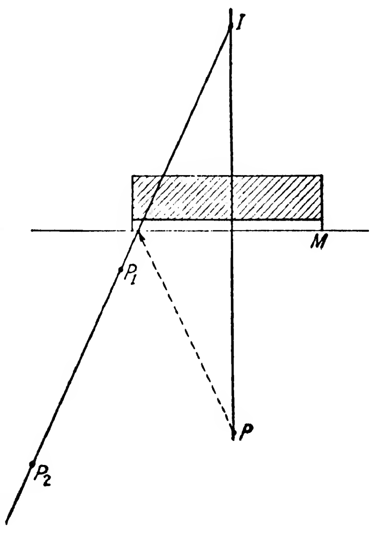


FIG. 62.—The law of reflection.

Remove the mirror; place a triangle or ruler so that it just touches both pins defining the direction of a ray; remove the pins and draw in the line using a very sharp pencil. Do the same for all other rays. Where do these lines intersect? How are the positions of object and image related?

At each point where an image line (reflected ray) cuts the position of the mirror erect a perpendicular to the mirror and draw the incident ray to this point. With a protractor measure the angles of incidence and reflection and tabulate. To what extent do your results confirm the law of reflection?

Exercise 59

THE CONVERGING LENS AND THE CONCAVE MIRROR

(Chapter XLIV)

Apparatus.—Converging lens and concave mirrors of short focal length; metal shield with arrow-shaped opening 2 cm. long to serve as object; meter stick, supports, lens holders, pins, ground glass with horizontal lines ½ cm. apart, sealing wax, frame with inverted pin to fit holder.

Direct Determination of Focal Length.—Mount the lens near one end and the screen near the middle of the meter stick, point the stick directly toward the sun or some distant object and slide the screen along until the image is sharp and clear. Read the

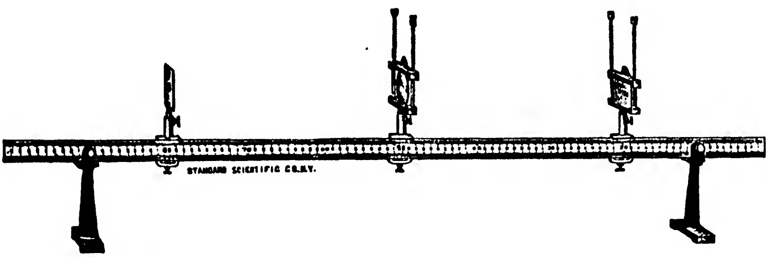


Fig. 63.—Optical bench with lens holders for Exercise 34.

position of lens and screen and compute the focal length. Make and record a number of such determinations using a different (distant) object in each case. Notice the distortion of the sun's image when the rays pass obliquely through the lens.

Object and Image Relations.—Support the meter stick horizontally in a clamp with the lens near the middle and the metal screen near the end. Place a lamp behind the screen or turn the whole bench toward a brightly lighted window and move the ground-glass screen along on the opposite side of the lens until a sharp image of the opening in the metal screen is formed. Record the positions of the object, lens, and image and note the sizes of image and object. Describe the image by use of the proper technical terms as *real* or *virtual, enlarged* or *smaller, erect* or *inverted.* Place the object at twice the focal length and repeat all observations, then move it about 5 cm. nearer the lens and repeat again.

The method of parallax which is often useful in locating images depends upon the fact that, if an observer moves at right angles

to the line of sight, nearby objects appear to be displaced in the direction opposite to his motion with respect to those farther away. As an illustration of this, hold a pencil vertically in front of the eye and in line with a corner of the room and note the effect of moving the head from right to left. This relative displacement is called "parallax." It follows that if two objects show no parallax they are at the same distance from the observer, *i.e.*, in the same plane.

Replace the object previously used by a pin which may be fastened point up to the lens holder by a bit of sealing wax, and place this pin slightly inside the principal focus. Look through the lens at the pin (or rather at its image) and adjust a second lens holder carrying an inverted pin until there is no parallax between this index as observed *over the top* of the lens and the image of the object pin as seen *through* the lens. Record the positions, and character of image as before.

Using each set of observations and the equation

$$\frac{1}{p} - \frac{1}{q} = \frac{1}{f},$$

compute the focal length of the lens and compare it with the value obtained by direct measurement. Also check the statement made in the text as to the relative sizes of image and object.

Repeat the observations using a concave mirror instead of the converging lens. In this work the axis of the mirror must be turned at a small angle with the meter stick which supports the object and the image thus thrown to one side in order that the screen may not cut off the incoming light.

For any one of the positions of the object make a careful scale drawing (p. 462, text) to locate the position of the image and compare the result thus obtained with the observed position.

Do not become so absorbed in measuring focal lengths that you fail to see the images themselves. Remember that the really interesting and important thing is not the focal length of this particular lens but the sorts of images formed by such lenses in general. Try a few things on your own account.

Exercise 60

THE SIMPLE MICROSCOPE

(Page 478)

Apparatus.—Meter stick with supports, two lens holders, card with fine print, coordinate paper, two or three short-focus lenses or magnifying glasses.

The Distance of Most Distinct Vision.—Hold the end of a meter stick against the chin and slide a printed card (which may conveniently be carried in a lens holder) along the meter stick until it is seen most clearly. Record and repeat several times. The average is your *distance of most distinct vision.* The lens system of your eye (aided by eyeglasses if you wear them) is such that a pencil of rays diverging from a point at this distance is focused on the retina without effort. *All microscopes and telescopes must bring to your eye light of this degree of divergence* if you are to see the objects examined clearly and without eye-strain. In other words, they must produce an image (in practice it is always a virtual image) at the distance of most distinct vision from your eye.

The Simple Microscope.—Mount a short focus, double-convex lens near one end of a meter stick and hold it close in front of one eye. Slide a printed card along the meter stick until it is most easily read. How far from the eye is the image? Make several trials with the lens in the same position and record. What is the ratio

$$\frac{\text{Image distance}}{\text{Object distance}}?$$

Describe the image in the usual technical terms. Use a second lens of different focal length. What difference is there in the images?

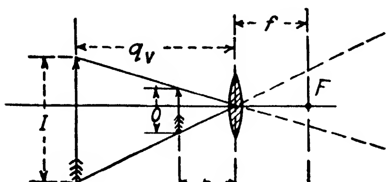


FIG. 64.—Magnifying power of the simple microscope.

Since the lens as here used must form a virtual image at the distance q_v of most distinct vision from the eye or (since the lens is close to the eye) from its own optical center the object must be placed so that (Fig. 64)

$$\frac{1}{p} - \frac{1}{q_v} = \frac{1}{f}. \qquad (1)$$

From similar triangles it may be seen that the magnification M is given by

$$M = \frac{I}{O} = \frac{q_v}{p}. \tag{2}$$

Since we wish to find the value of q_v/p, we may multiply each term of equation (1) by q_v and transpose, thus finding

$$M = \frac{q_v}{p} = \left(\frac{q_v}{f}\right) + 1. \tag{3}$$

How does the magnifying power of the simple microscope depend upon its focal length? Does this agree with your observation above?

To check the above results replace the printed card by a piece of coordinate paper. Set it so that a clear, magnified image is seen through the lens. Now keep both eyes open and look through the lens with one eye and past it with the other. After a few trials you may be able to see the magnified and unmagnified images overlapping one another and determine the magnification by counting the number of squares seen with the unaided eye which equal one square of the magnified image. Make several counts and compare with your previous results. (This direct determination is possible only if the magnifying power is rather low (two or three diameters) since with higher magnification the object will be so close to the eye that no clear image can be seen outside the lens.) Where must the object be placed (in relation to the principal focus) for the simple microscope? Have you noticed any distortions or coloring of images in this work? Rotate the lens about a vertical axis so that the beam of rays makes a considerable angle with the principal axis and note the effect.

Exercise 61

THE COMPOUND MICROSCOPE

(Page 479)

Apparatus.—Two converging lenses of short focal length, meter stick with supports, three lens holders, card with circular opening, coordinate paper.

Determine the focal length of each of the two lenses. Place the one having the longer focal length at one end of the meter stick to be used as the *eyepiece.* Using the relations derived in

the previous exercise, compute the distance d from the lens to an object which will give an image at the distance of most distinct vision. The "object" in this case is to be a real, enlarged image produced by the other lens (the objective). The next problem is to decide where to place the objective since there are an infinite number of positions of objective and object which would form an image at the desired place. The choice must be made arbitrarily (in actual microscopes a standard tube length is used) and, for present purposes, may well be four times the focal length of the objective ($4f_o$) from the eyepiece. The object position (*i.e.*, dis-

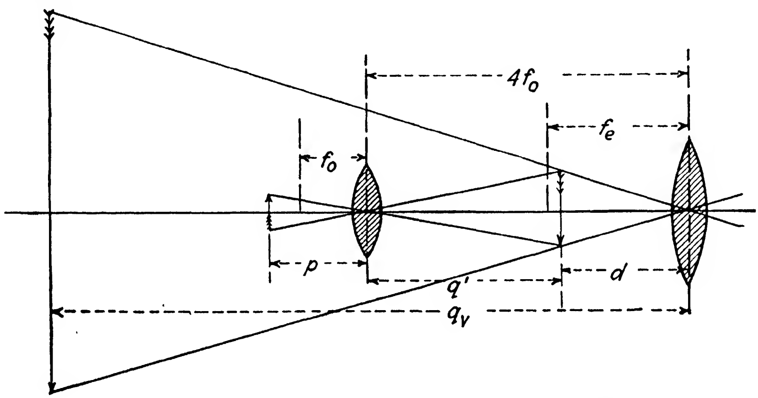


Fig. 65.—Diagram illustrating computations for Ex. 61.

Assumed $f_e = 10$, $f_o = 5$, $q_v = 40$.[1]

To find d, $\quad \frac{1}{d} - \frac{1}{40} = \frac{1}{10}, \quad d = 8$

To find p, $\quad 4f_o - d = 20 - 8 = 12 = q'$

$$\frac{1}{p} + \frac{1}{12} = \frac{1}{5}, \quad p = 8.7$$

tance the object must be placed from the objective) may now be computed from the lens equation which for this purpose becomes,

$$\frac{1}{p} + \frac{1}{q'} = \frac{1}{f_o}$$

(since both q' and f_o lie on the opposite side from p). In this equation q' (the distance from the objective to the image which it produces) must be equal to the distance between lenses less the distance from the eyepiece to that image. This latter value (d) was computed above; *i.e.*, $q' = 4f_o - d$.

[1] The distance of distinct vision is here taken as 40 to simplify computation. Twenty-five centimeters is usually assumed although this actual value will be different for each individual.

Place the lens holder carrying the coordinate paper at the calculated position. If the image seen through the eyepiece is not satisfactory, try to improve by "focusing," *i.e.*, by slightly moving the object until the best results are obtained. When the adjustment is secured, determine the magnifying power as directed in the previous exercise and compare with the theoretical value

$$M = \frac{hD}{f_o f_e}.$$

Here h is the distance between lenses, D the distance of most distinct vision f_o and f_e the focal lengths of the objective and eyepiece.

Look for evidence of distortion and aberration in the images produced by this simple lens combination. Try the effect of placing a card carrying a small circular opening just behind the objective.

Exercise 62

USE OF DIFFRACTION GRATING[1]

(Chapter XLVII)

Apparatus.—Spectrometer, replica grating, spectrum tubes, small induction coil, sodium flame, supports.

If the spectrometer has been adjusted by the instructor the only adjustments which the student need make are to move the eyepiece in or out until the cross-hairs are most distinctly seen, and then, with the telescope pointing directly at the illuminated and rather narrow slit, to focus it until the image of the slit is sharp and there is no parallax between the image of the slit and the cross-hairs. When this adjustment has been made the instrument is ready for use.

Reading the Verniers.—Before making any settings it is best to become familiar with the scale and verniers so that readings can be made rapidly and easily. The principle of the circular vernier is exactly like that of the ordinary vernier but the readings are somewhat complicated by our awkward system of measuring

[1] NOTE.—Since it is the purpose of this exercise to allow the student to measure a considerable number of wave lengths it is assumed that the spectrometer will have been adjusted for parallel light and the grating placed in the proper position by the instructor.

angles in degrees, minutes, and seconds—three units for a single quantity. Examine the *scale*. What is the value of the smallest scale division on the instrument in use? Set the verniers so that the 0° mark coincides with some numbered scale division. How many divisions on the vernier? To what fraction of a scale division is one vernier division equal? In many instruments 20 major vernier divisions cover 19 scale divisions each of which is equal to 20 min. and each of these larger vernier divisions is divided into three parts. The procedure of reading is exactly as with the ordinary vernier. Read and record the

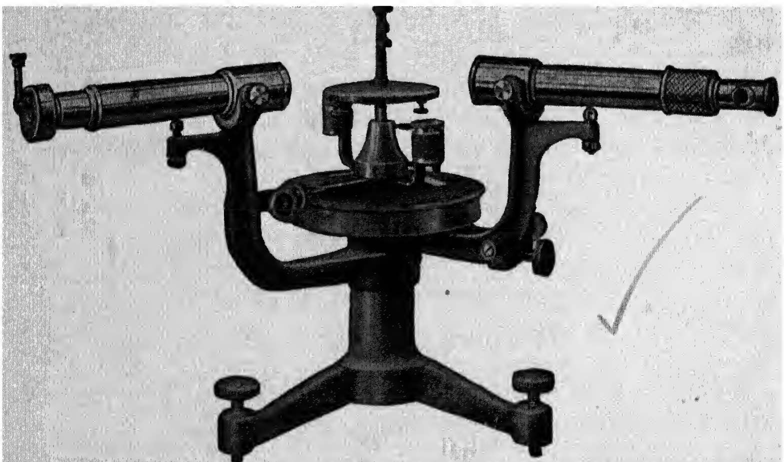


FIG. 66.—Spectrometer.

scale value next below the zero of the vernier. Locate the vernier mark which coincides with a scale mark. In the case described major vernier divisions up to this point correspond to minutes and the smaller divisions to 20 sec. each. A good method is to record readings as follows:

Scale	273°	40′	
Vernier		4	40″
Position	273°	44′	40″

Put an incandescent lamp in front of the slit and examine the spectrum. Note the undeviated slit image. How many orders can you see? Note positions of various colors in the first order. Make approximate settings on the extreme red and the extreme violet of the first order on each side, and compute the corresponding wave lengths. (The angle of deviation θ is half the

angle through which the telescope is turned when measurements are made in this way.)

Put a flame colored with sodium in front of the slit (not too close). Set on the diffracted image to the left and close the slit until it becomes very narrow. If the adjustments are satisfactory you should be able to see that this line is really two lines. Set the cross-hairs carefully on each of these in turn, using the slow-motion screw below the telescope for final adjustment; and read *both* verniers. Repeat these settings and then turn to the right-hand image and make the same determinations. Compute the wave lengths of the two components using the grating constant (lines per centimeter) as marked. Compare with tables (Handbook). Use the vacuum tubes and measure a number of lines. If possible, throw a beam of sunlight on the slit and measure a few of the more prominent dark lines, and see if you can identify them from the tables.

Tabulate all your measured wave lengths together with the tabular values. What degree of accuracy do you obtain? Is there any systematic difference between your values and those in the tables? If so it is likely to be due to an inaccuracy in the grating constant. How could you determine the amount of this correction? To what fraction of a centimeter could you "measure" the grating constant by working backwards from your data; *i.e.*, by assuming the wave length as known and the grating space as unknown?

GROUP XI

RADIOACTIVITY

Exercise 63

(Chapter LIV)

Apparatus.—Electroscope with observing microscope, charging rod, Bunsen burner, $\frac{1}{4}$-in. iron rod, graphite rod, radioactive ore, 1 mg. radium if available, X-ray tube, source of ultra-violet light, stop watch, glass tube attached to large rubber bulb.

Air, under ordinary conditions, is an excellent insulator but is rendered conducting by any one of a considerable number of "ionizing" agents which produce charged particles, *ions*, in the normal air. These ions are, like all small electrified bodies, attracted to charges of the opposite sign and repelled by those of like sign. Thus, when any charged body is exposed to ionized air, a double stream of ions is set up in its neighborhood; ions of the same sign as the charge flow away, while those of the opposite sign fall upon the charged body and neutralize the original charge. The charged body is discharged at a rate which depends upon the degree of ionization of the air, *i.e.*, upon the number of ions per cubic centimeter of air and the intensity of the electric field.

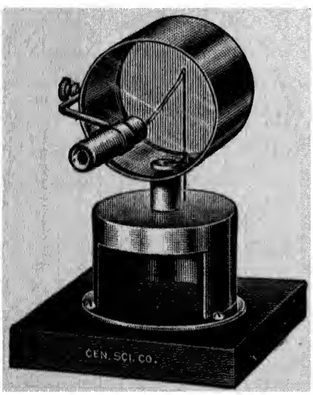


FIG. 67.—Electroscope for radioactivity study.

If ions are being produced at a steady rate and the electric field is sufficiently intense, the ions will be removed as rapidly as they are formed. In this case the rate of discharge of the electrified body is proportional to the effectiveness of the ionizing agent. It is the purpose of this exercise to afford you an opportunity of observing some of these phenomena.

The gold-leaf (or aluminum-leaf) electroscope in its modern form consists of a carefully insulated brass plate which carries a narrow strip of gold or of aluminum leaf which is repelled from the plate when both are charged. For quantitative work this leaf is observed through a long focus microscope having a scale in the eyepiece. The rates at which the image of the leaf moves over this scale afford a means of comparing the ionization of the air under different conditions. In the form shown this "head" is attached to an "ionization chamber." The conductivity of air in this chamber is to be tested. Charge the electroscope and adjust the observing microscope so that the image of the leaf is clearly seen near the lower end of the scale. Read the position of one edge of the image, allow the instrument to stand from 3 to 5 min. in a room away from radioactive materials and read again. If the electroscope is well insulated there will be little change in the position indicating that the normal air is but slightly ionized.

Ionization by Flame.—Open the door of the ionization chamber, bring the flame of a Bunsen burner near it and by means of the rubber bulb and glass tube blow the air from above the flame into the chamber. How does this affect the rate of discharge? Why?

Ionization by Glowing Solids.—Heat one end of the iron rod as strongly as possible in the flame and hold between the plates. Note and explain any effect. Try the same test with a glowing graphite rod.

Ionization by X-rays and Ultra-violet Light.—If possible, take the electroscope into a room where an X-ray tube or a source of ultra-violet light is in operation and observe the effect. The instructor will operate these for you.

Ionization by Radioactive Materials.—You have two samples of radioactive ores. Set the metal pan on a clean sheet of paper, fill it level full of one ore (A) scraping off any excess. Wipe the outside of the pan carefully, place in the ionization chamber and determine the time required for the leaf to fall over ten divisions of the scale. Make three trials and average. Return this ore to its bottle and repeat with the second sample (B). *Be very careful not to mix the two samples or spill any of the ore in the laboratory.*

If the electroscope is well insulated, the natural leak will be so small that it may be neglected. Under these conditions the rates of leak afford a moderately accurate means of comparing the amounts of radioactive materials in the two ores if these are

similar in character, ground to equal fineness, and not too different in radioactive content. Under such conditions, the *rates* of fall are directly proportional to the radioactive content of the ores and hence the latter are inversely proportional to the times required for the leaf to fall over the same portion of the scale.

This follows from the following facts: (1) under the conditions of the experiment ions are being removed as fast as they are formed; (2) the average charge on each ion is constant; (3) when the leaf falls over the same part of the scale it loses a definite quantity of electricity; (4) the number of ions formed per second in the air above the tray is proportional to the radioactive content of the ore. Thus, if each ion carries an average charge e, the numbers formed per second are n_1 and n_2, and the times of fall t_1 and t_2, respectively, we have for the quantity q of electricity lost by the electroscope,

$$q = n_1 e t_1 = n_2 e t_2,$$

or

$$\frac{n_1}{n_2} = \frac{t_2}{t_1} = \frac{\text{radioactivity of first ore}}{\text{radioactivity of second ore}}.$$

Check this conclusion by comparing your results with the percentages of U_3O_8 contained in the ores.

Ionization by Radium.—If a tube containing 1 mg. of radium is available set it at a distance of 1 meter from the closed ionization chamber and note the rate of fall of the leaf. Try moving the radium away until its effect is no longer noticeable. At what distance is it detectable? An interesting variation is to have the instructor hide the radium and see if you can locate it by means of the electroscope. Why is the electroscope seemingly less well insulated and also more sensitive as a detector of radium when attached to a large chamber?

INDEX

I

J

K

L

M

N

O

P

R

S

T

U

V

W